AD-758 005

EXPLOSIVE CLADDING MAJOR CALIBER GUN BARRELS. FEASIBILITY STUDY

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October 1972

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REPORT NO. MT 012
OCTOBER 1972

EXPLOSIVE CLADDING MAJOR CALIBER GUN BARRELS

FEASIBILITY STUDY

A MANUFACTURING TECHNOLOGY PROJECT
FOR THE
INDUSTRIAL RESOURCES AND FACILITIES DIVISION, ORD-047
NAVAL ORDNANCE SYSTEMS COMMAND

FINAL REPORT

NAVAL ORDNANCE STATION
LOUISVILLE, KENTUCKY 40214

67

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Ordnance Station Louisville, Kentucky 40214	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP --

3. REPORT TITLE

Explosive Cladding Major Caliber Gun Barrels; Feasibility Study

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report

5. AUTHOR(S) (First name, middle initial, last name)

Richard P. Grollo

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1972	61	--

8a. CONTRACT OR GRANT NO. b. PROJECT NO. PO 9-0193 & PO 9-0195 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) MT-012 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Ordnance Systems Command (ORD 047) Industrial Resources & Facilities Division Washington, D. C. 20360

13. ABSTRACT

The purpose of this program was to determine the feasibility of, and the parameters for, explosively cladding an AISI 4130 steel liner to the inner diameter of an expended 5 inch diameter gun barrel.

The initial work consisted of developing the parameters for cladding flat plates; later these parameters were expanded to include cylindrical cladding of expended portions of 5 inch diameter gun barrels.

Seven experimental tests were conducted using expended gun barrel portions. Although these tests proved the feasibility of gun barrel cladding, two attempts to explosively clad a full length liner into a 5 inch gun barrel proved unsuccessful.

Details of illustrations in this document may be better studied on microfiche.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
High Energy Rate Forming (HERF)						
Explosive Cladding						
Slurry Explosives						
Shock Welding						
Gun Barrel Cladding						

ABSTRACT

This report presents the results obtained from experiments conducted in an attempt to explosively clad a steel liner to the inner diameter of an expended 5 inch diameter gun barrel.

The purpose of this project was to determine the feasibility of, and the parameters for, explosively cladding a liner into the bore of expended gun barrels such that machining stock would be provided for remachining the bore.

The initial work consisted of developing cladding parameters for flat plates of AISI 4130 steel which is similar in chemical composition to that of naval gun barrels. After developing the cladding parameters for flat plate, seven experimental tests were conducted using expended portions of 5 inch diameter gun barrels. These tests proved the feasibility of gun barrel cladding.

NOSL made two attempts, unsuccessfully, to explosively clad a full length 5 inch diameter gun barrel. The results of our efforts indicate that additional work will be required to design and build a more stringent restraining die and to further our investigation to definitely define the explosive cladding parameters.

FOREWORD

This is the final report of work completed under NAVORDSYSCOM'S Project Order PO 9-0195 issued to determine the feasibility of, and the parameters for explosively cladding a steel liner into the bore of expended gun barrels such that machining stock would be provided for remachining the bore. This feasibility study was performed by the Advanced Technology Branch of the Naval Ordnance Station, Louisville, Kentucky. Funds were provided by the Industrial Resources and Facilities Division of NAVORDSYSCOM (ORD 047) under the Manufacturing Technology Program.

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1. INTRODUCTION

1.1. Basic Idea

The idea of explosively cladding a steel liner to the inner diameter of an expended gun barrel was conceived by personnel of the Naval Ordnance Station, Louisville (NOSL). The magnitude of this operation and the time required to ultimately deliver refurbished gun barrels to the Fleet were well realized. With this in mind, the idea was conveyed to ORD 0472 where it was decided that sufficient evidence did exist to realize a successful conclusion to the experimental project.

1.2. Subcontractor

A contract was negotiated with Aerojet-General Corporation for an initial investigation of this project and to indoctrinate NOSL personnel in techniques of explosively cladding metals. Appendix A is a resume of this contract and a report of the data obtained. In February 1968, Aerojet-General proposed an additional program to lengthen this investigation into a four-phase program. See Appendix B, a work statement of this proposal. Due to the limited funds allotted for this program, only Phases I and III were accepted. The former Phase I entailed cladding a steel liner to a 5 inch inside diameter, 36" long gun barrel section, while the latter, Phase III, determined the liner bond integrity using non-destructive techniques.

1.3. Sub-scale Model

An unsuccessful attempt to clad a full length gun barrel by NOSL personnel prompted a sub-scale gun barrel cladding program. Results of this program along with other data led to the recommendations of this report.

From the foregoing, the work statement has been fulfilled in the following manner:

Investigate cladding a AISI 4130 steel liner to a machined 5" diameter gun barrel.

2. ELEMENT OBJECTIVE

Investigate cladding of AISI 4130 steel plates to determine practicability of proceeding with project.

COMMENT: Completed.

Design restraining dies and investigate restraining materials to support barrel during cladding operations.

COMMENT: Appendices A and B give background material on restraining dies that have been used to support barrel sections during cladding operations.

Explosively clad a AISI 4130 steel liner to a 12" length section of 5" diameter barrel of Rockwell hardness 35 - 40 "C" scale. Proceed to 40" length section of barrel following the established procedures.

COMMENT: Completed

Conduct a non-destructive inspection of gun barrel cladding to determine degree of clad interface.

COMMENT: Non-destructive inspection results as listed in Appendix B gives every indication that this method may be used to inspect full length barrels.

Clad a full length barrel and prepare it for machining.

COMMENT: The experiment to clad a full length barrel resulted in partial destruction of the gun barrel. This failure resulted due to our attempt to utilize a minimum size restraining die. If this die had extended aft to the slide diameter, the consensus is there would have been no barrel failure and successful cladding might have resulted. This program must prove the economics of cladding expended gun barrels, therefore, from an overall cost standpoint, it was impractical to fully contain the gun barrel. Further experimentation was necessary and a request to extend the program was granted by ORD 0472.

2.1. The Cladding Program

The initial study, conducted by Aerojet-General's Material Technology Division, was monitored by NAVORDSTALOU for a twofold purpose. Since the Station was at that time a comparative infant in explosive metalworking, it was felt that overseeing the process would in itself be useful for future applications. Secondly, should the liner cladding prove successful, the process and application would be available to competitive industries. The final phases of the program were to be conducted by personnel at NAVORDSTALOU.

The evaluation of explosive bond quality in a section of 5" diameter gun barrel by Aerojet-General's Material Technology Division indicated that the process was indeed feasible (Appendix B). The longest clad length of barrel section was 37.83" long; ultrasonic inspection confirmed that cladding occurred in over 83% of the barrel area. The explosive and the set up process left much to be desired if this process was to be applied to a full length gun barrel.

2.2. Explosive Loading

Cladding cylindrical tubes of short lengths do not pose any major problems. The explosive must be packed to eliminate any void which may cause the Monroe or "shaped" charge effect. This could burn a hole through the tube wall. Also, the charge density must be maintained to insure a constant detonation velocity.

The previous method which had been most reliable was to weigh the amount of explosive charge that is to be contained in a certain volume, then tamp the explosive charge into this volume to obtain the desired density. For ease of tamping, this chore was done in increments of one-inch of tube length. This method would be prohibitive for 25 feet length gun barrels.

The above method was satisfactorily used by Aerojet-General and NAVORDSTALOU to develop the cladding parameters for short barrel sections. However, this procedure proved unsatisfactory for lengths greater than three feet.

2.3. Slurry Explosive

The mining industry had experienced similar problems when loading "bore" holes with dynamite. It was necessary to tamp the charge into the hole to insure that maximum shock would occur. When slurry explosives were developed, they could be brought to the "bore" hole in tank trucks, then pumped into the hole and detonated. The "slurry" consistency explosives are very stable. It can be transported in separate tanks, mixed at the site and then pumped into the "bore" holes prior to detonating.

The Inter-Mountain Research and Engineering Company (IRECO) had been funded by ORD 03 (R&D) to improve slurry explosive for use in ordnance applications. This firm was very cooperative and readily supplied samples to NAVORDSTALOU for evaluation. The explosives tested exhibited characteristics suited to the high energy metalworking field. Some of these characteristics are:

a. A relatively low detonation velocity

b. The mix consistency is suited for pouring, and settling is minimal.

c. The unmixed explosive components can be air freighted.

d. After mixing, the explosive is stable and easily detonated with a booster charge and blasting cap.

NAVORDSTALOU obtained a sufficient quantity of the slurry explosive to develop the parameters necessary to continue the program on short barrel sections.

Cladding experiments which required over one pound of explosives were conducted at the Naval Ammunition Depot (NAD) Crane, Indiana, located approximately 100 miles north of NAVORDSTALOU. The explosive forming facility at NAVORDSTALOU is within the city limits and about three hundred yards from an apartment complex, thus necessitating using NAD's remote ranges for larger explosive cladding shots.

3. GUN BARREL CLADDING

Following is a report of comparative cladding results obtained on barrel sections and a full length barrel by using slurry and other type explosives.

The results of these experiments have been summarized in Table 1; Table 2 lists the characteristics of explosives used for the experiments. Of the six samples tested, S1 was insignificant and was therefore omitted from the data.

The bulk of explosive cladding data concern flat plates with little information which may be applied to tubular configurations. This program began on the basic assumption that the parameters involved in tubular cladding would be very similar to those for plates.

A graph, shown in Figure 1, was developed by Battelle Memorial Institute. These curves provide a means of determining the amount of explosives required to obtain cladding for a given flat plate configuration. According to these data, the amount of explosive required per unit area of material to be clad is related to the yield strength, density, thickness of the flyer plate and the standoff distance between the flyer and base plates at the time of detonation. This relationship yields the load Factor B used in the following discussion:

In flat plate cladding (Figure 2) only a percentage of the explosive energy is used in the cladding process; the remainder is dissipated into the atmosphere. In the tubular case (Figure 3), the confined explosive contributes more energy to useful work. Sample S2 was designed to fall within the "acceptable cladding range" of Battelle's curve for flat plates. Fragmentation was anticipated in S2 due to the higher efficiency of the explosive energy; as a safety precaution, a sulphur-filled restraining die was used to minimize shrapnel. As noted in Table 1, fragmentation anticipations were correct.

S3 was designed to have a load factor of approximately 65% of that used for S2. Due to material variations, the amount of explosive actually loaded resulted in a load factor of approximately 75% of S2. As shown in Table 1, cladding did occur and was verified by microscopic examination of the interfaces in several cross-sectional cuts.

It is noteworthy that different explosives were used for these samples to determine which would be most convenient to use. Although using TNT, sample S3 did provide a load factor to achieve cladding. It was obvious the slurry-type explosive was the most suitable, therefore, it was used for all subsequent tests.

Sample S4 was set up to confirm the independence of explosives by using the same load factor as S3 but with the preferred slurry explosive. The test was made, and visually, it appeared that cladding occurred.

As demonstrated by samples S2 and S3, the Battelle curves could not be directly applied to the cladding of tubular configurations. Therefore, the determination of load Factor "B" now appeared to be of less importance.

For this reason, it went practically unnoticed that, with the increase of liner thickness from .3125 inches on sample S3 to .406 inches on the sample S4, the load Factor B indicated an areal load increase of 1.5 grams per square inch. It seems reasonable to assume that some similar relation would hold true for tubular configurations. Sample S4 apparently cladded; however, the loading was approximately .82 gm/in^2 less than S3.

Sample S5 was used in the preliminary trial prior to our efforts at cladding a full length barrel. The preliminary trial verified the parameters and provided, due to its increased length, an abundance of test specimens. Cladding was evident by microscopic and photomicrographic inspection of the liner. The clad portion of the sample was tested by cutting a 3-1/2 inch wide ring from the sample and subjecting the edge of the liner to a shear force. Partial failure was noted at a 400 ton press force. This is the approximate shear stress of 103,000 psi. No difficulties were encountered when the rifling was electrochemically machined in a 12-inch long specimen of this sample.

As in the case of sample S4, the load factors of both samples were equal, but the areal loading of sample S5 was approximately equal to sample S3. In the case of sample S5, cladding was verified; but one aspect that precludes any generalization of the three samples is the fact that sample S5 was restrained in concrete, while no restraint was used for samples S3 or S4.

All aspects of the program appeared to be progressing satisfactorily. The next step was the cladding of a full length barrel. The assembly for sample S6 was basically as shown in Figure 4. The restraint at the muzzle end was fashioned from an expended 8 inch diameter gun barrel. The barrel section was tack welded as shown and the void between the walls filled with molten Wood's metal.

The experiment with sample S6 resulted in the barrel rupturing approximately 84 inches in length, originating about 30 inches from the muzzle end. The restraint failed in approximately half of its length. The consensus was with adequate restraint, cladding would have been successful; it appeared that the remainder of the barrel had been clad. (See photographs Figure 5).

Subsequent inspection indicated that very little cladding occurred and it was believed that when rupture occurred the effective pressure was reduced to the point where little or no useful energy remained.

Sample S7 was fabricated to verify this theory. It appeared that cladding had occurred throughout the length of S7, but subsequent inspecting proved other than an exceptional press fit; no significant cladding had occurred.

After the trial sample S6, stress analysis was made to determine the extent or size of restraint required to effectively contain a full-length gun barrel. According to the resulting calculations, the die mass and fixturing was outside the realm of practicality.

Obviously a more meaningful method was necessary, therefore, a subscale barrel test was initiated, in order that some parameters could be investigated on a reduced scale.

A leading researcher in the field of explosive metalworking was contacted on the matter of restraints. He stated that in his opinion the occurrence of cladding was independent of the restraint used. As a test for his theory, a flat plate experiment was conducted at NAVORDSTALOU. Since the anvil or steel plate backing up the flat plates could be considered the restraint, the anvil was eliminated.

First, two plates were clad using the anvil approach to verify the load parameter; then two identical plates, using the same parameters, were placed on one and one half feet of shock absorbent material, cladding did occur. The same parameters were then duplicated on two plates suspended in air; cladding occurred! Therefore, it appears that the restraint plays no significant role in the cladding process.

4. SUBSCALE BARREL TEST

Four 10" length sections of AISI 4130 aircraft quality seamless steel tubing with a 3" outside diameter and a 1" wall were used for the subscale barrel test. Standoff, the distance between the two plates prior to detonation, was varied by machining a .010 inch per inch taper into the central 8 inches of the tubes inside diameter. A liner tube of the same material measuring 9 inches long by 1 inch outside diameter with a .083 inch wall was centered in the inside diameter of the larger tube (Figure 6).

The tubes were clad using slurry explosive with an areal loading of 2.5 gm/in^2. Detonation propagated from the larger inside diameter taper in samples #4 and #5 and from the smaller inside diameter taper in samples #6 and #7. This was believed to normalize the effects of explosive initiation.

The clad tubes were cut radially into eight equal, wedge-shaped sections to expose the liner for inspection and testing. The radial sections were cut into one inch long specimens for testing on an O-T shear testing machine. A fixture was designed and fabricated to facilitate testing the 184 segments.

Before each segment was tested, it was inspected for apparent cladding, impact fracture, true length and effective width. These measurements were used to calculate failure force per unit area (pounds per square inch).

Each segment was then inspected to determine cause of failure and range of force necessary for shearing to occur. Figure 7 is a graph comparing the results of the shear test.

As a result of shear tests conducted on the segments, two critical factors were discovered that influenced good cladding.

The end from which detonation was initiated appeared to greatly influence cladding. In the two tubes where initiation occurred at the smaller inside diameter, shear figures were roughly 2,000 pounds per square inch higher.

Cladding did not occur in the areas of little or no standoff and excessive standoff. Fracturing of the liner occurred at these locations. In the latter case, this was opinioned to be a result of the excessive velocity attained by the liner, whereas in the former case momentum energy was minimal and the excessive expansion energy fractured the material.

Figure 7 indicated that acceptable cladding had occurred in tube ring area "C", which corresponds to a standoff distance of .130 inches. The ratio of standoff distance to liner wall thickness for this case was .130/.083 or 1.566. In tube ring area "F", shear readings rose substantially over tube ring areas "D" and "E" in tubes #4 and #5. These readings were less uniform when compared with tubes #6 and #7 and felt to be a function of the direction of initiation. The interface quality of tubes #4 and #5 was inconsistent because of the choking action imparted by the gradually decreasing standoff. The slight increase in standoff as seen by the interface of tubes #6 and #7 allowed a steady uniform surface collision to occur which resulted in the stronger bond.

5. CONCLUSIONS

Considering all the samples and tests, it appears the feasibility of gun barrel cladding has been proven with respect to the achievement of cladding tubular configurations. At this time only short lengths, up to 36" of a 5" diameter gun barrel, have been successfully clad. A full length barrel may be clad by using some undetermined type of restraint, or possibly a decreasing explosive load could be utilized to lower the internal expansion pressure. Another possibility is that cladding might be accomplished in say six linear feet increments.

Most gas erosion of gun barrels occurs in the first four feet beyond the origin of the bore although some erosion has been noted in the muzzle portion. In the course of the program, sections for cladding were obtained from the muzzle portion of expended barrels. Since this is the thinnest wall section of the barrel, any cladding obtained without restraint may be duplicated in the heavier wall sections.

New barrel forgings are supplied in lengths greater than required for the finished length. These "cropped" ends are removed from the muzzle end of the barrel just prior to final machining and are used for evaluation of alloy, strength, etc.

Samples of both breech and muzzle ends were used to evaluate charge loading, standoff, and other parameters. A configuration was developed whereby short liners with tapered ends were "patch" clad inside the ends with very little expansion of outside diameter. The comparative metallurgical findings are included in Appendix C.

The subscale barrel tests indicated the barrel length to diameter ratio is a very important parameter when explosives are employed to clad cylinders internally. Namely, if a cylindrical charge has an internal axial channel, the detonation is accompanied by the flow of gas in the channel; this strongly affects the detonation process. The air enclosed in the channel is driven forward by the detonation gases in a compressed layer with a high temperature, high pressure and a steep shock front. This layer compresses the explosive before the detonation front and, as a result of the increased density, the detonation velocity becomes greater than that obtained in an unconfined homogeneous cylindrical charge with the same density. During the internal cladding of long tubular lengths, i.e. gun barrels, this appears to be the dominating effect.

Since this might indicate only short sections of barrels can be clad, this leads to the idea of a cladding process whereby sections of eroded or tool damaged barrels can be "patch" clad then put in service or used for training.

It is well to note that considerable interest has been created throughout the industry in the use of a slurry type explosive "pioneered by Naval Ordnance Station, Louisville," for tubular cladding.

6. RECOMMENDATIONS

A recent change in propellant has markedly decreased gun barrel failures attributable to gas erosion. The problem of fatigue failure from crack propagation is of major concern and is being investigated.

Heat checkering in the first five feet at breech end of the barrel is opinioned to be a major contributing factor to fatigue failure, therefore it is recommended studies be continued with explosively cladding this portion of gun barrels. The studies should determine which alloys, exhibiting high heat checkering resistance, are suited for gun barrel liners. The program scope should also determine if barrels or portions of barrels can be clad with the selected alloys and a process established whereby new manufactured barrels or barrel portions can be explosively clad.

SAMPLE NUMBER	SAMPLE LENGTH (INCHES)	LOAD FACTOR B_1 (#2/INS) (FROM FIG. 1)	EXPLOSIVE CHARGE LOADING (GRAMS/INS)	EXPLOSIVE TYPE	RESTRAINT	COMMENTS
S2	12	55	12.2	DBA-10HV	3/8" TK. STEEL SLEEVE (SULPHUR BACK-UP)	BARREL SECTION & DIE FRAGMENTED
S3	12	55	8.82	TNT	NONE	CLADDING-VERIFIED BY VISUAL & MICROSCOPIC INSPECTION
S4	12	71.4	8.0	DBA-10HV	NONE	APPARENT CLADDING NOT VERIFIED
S5	35	71.4	9.08	DBA-91	CONCRETE	CLADDING-VERIFIED BY VISUAL & MICROSCOPIC INSPECTION. 400 TON SHEAR TEST, SECTION ELECTROCHEM MILLED
S6	FULL LENGTH BARREL	71.4	8.8	DBA-91A	PARTIAL STEEL WITH WOODS' METAL FILL	PARTIAL RUPTURE INSIGNIFICANT CLADDING
S7	42	71.4	9.08	DBA-10HV	NONE	INSIGNIFICANT CLADDING

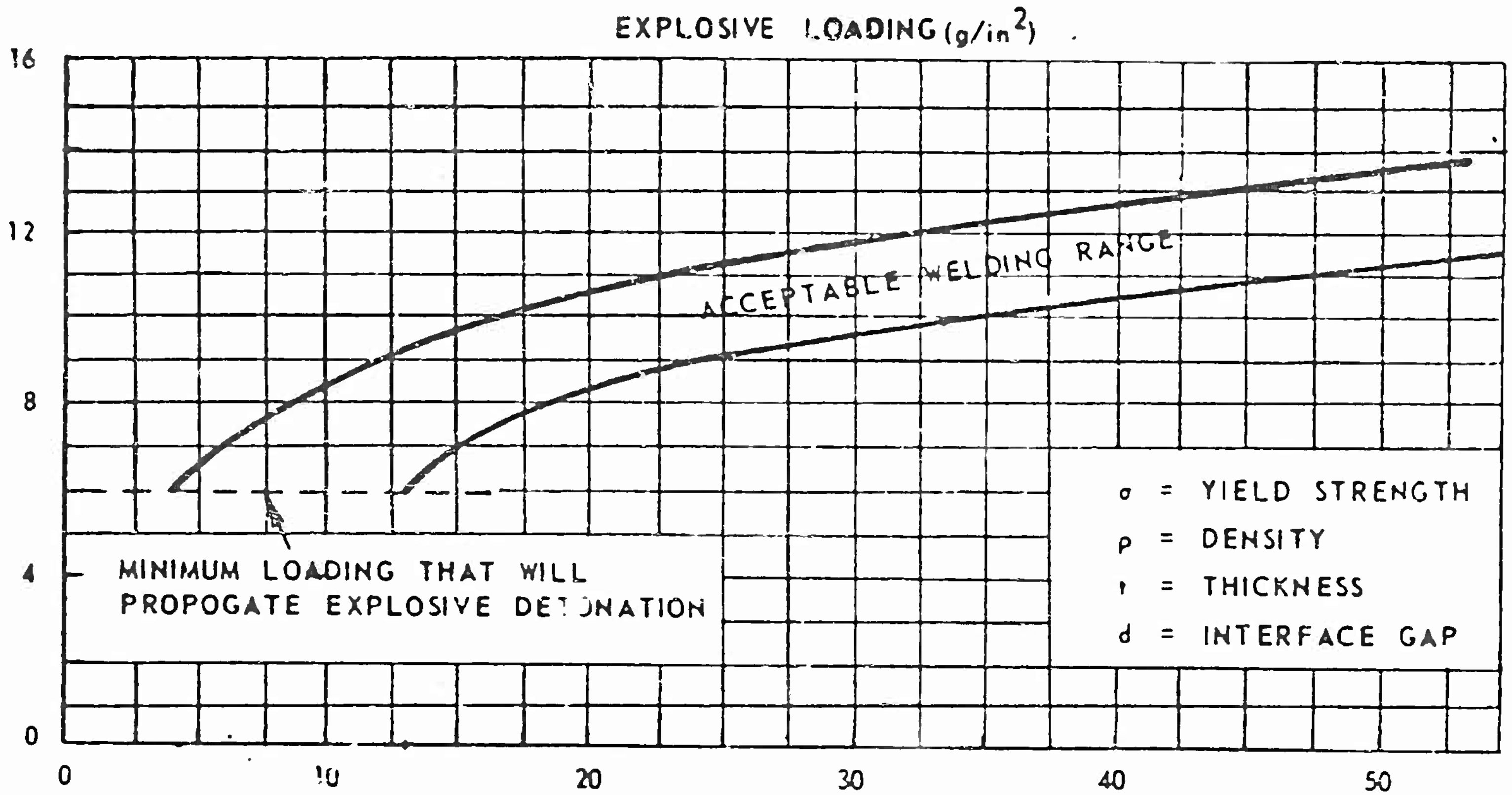
SAMPLE TEST DATA

TABLE 1

EXPLOSIVE	DETONATION PRESSURE (KBAR)	DETONATION VELOCITY (FT/SEC)	DENSITY (GM/CM^3)	CONDITION
TNT (GRANULATED)	120	19,000	1.0	HAND TAMPED
DBA 10HV (SLURRY)	35.7	11,090	1.25	POURED
DBA-91 (SLURRY)	49	11,811	1.5	POURED
DBA 91A (SLURRY)	100	15,000	1.45	POURED

EXPLOSIVE CHARACTERISTICS

TABLE II

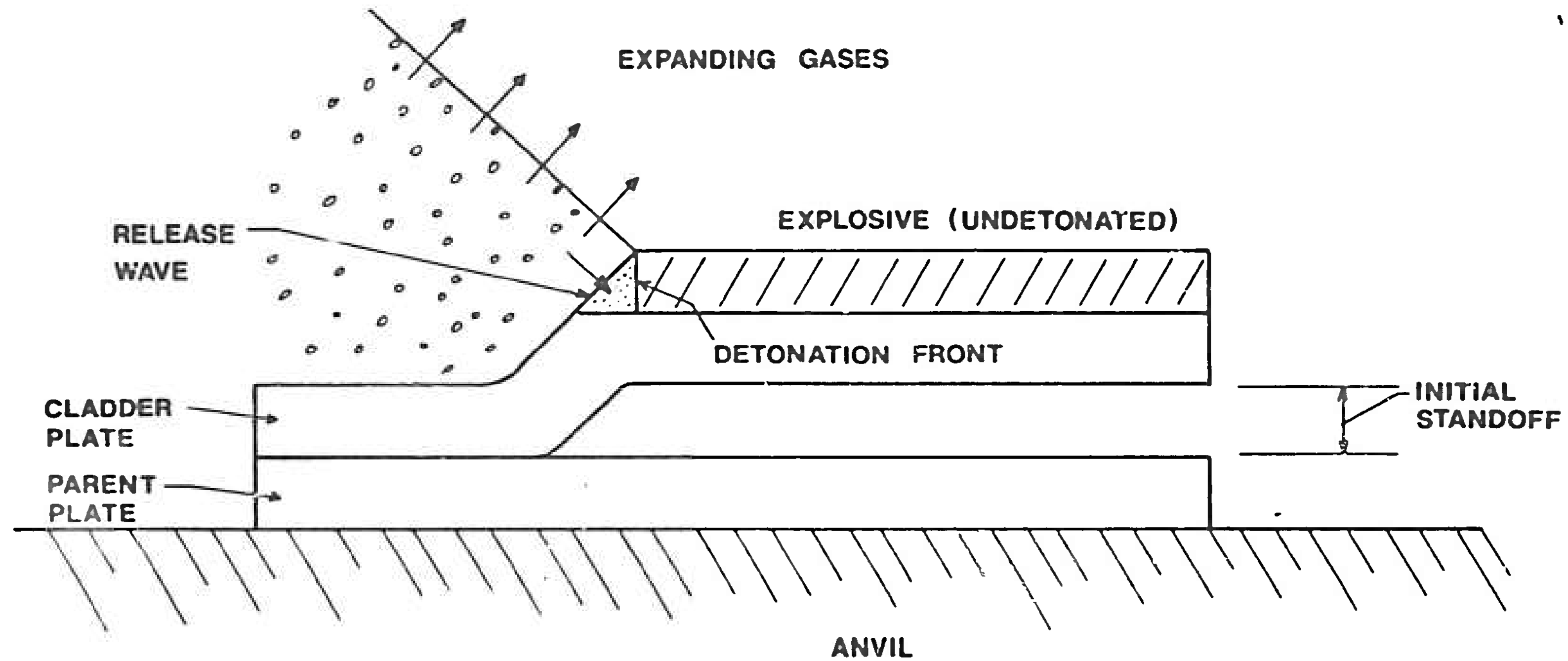


$B = \frac{\sigma \rho t}{d} \times 10^{-3}$ lbs^2/in^5, load factor

RELATIONSHIP OF THE IMPORTANT PROCESS VARIABLES FOR EXPLOSIVE BONDING WITH A LOW-DETONATION-VELOCITY EXPLOSIVE

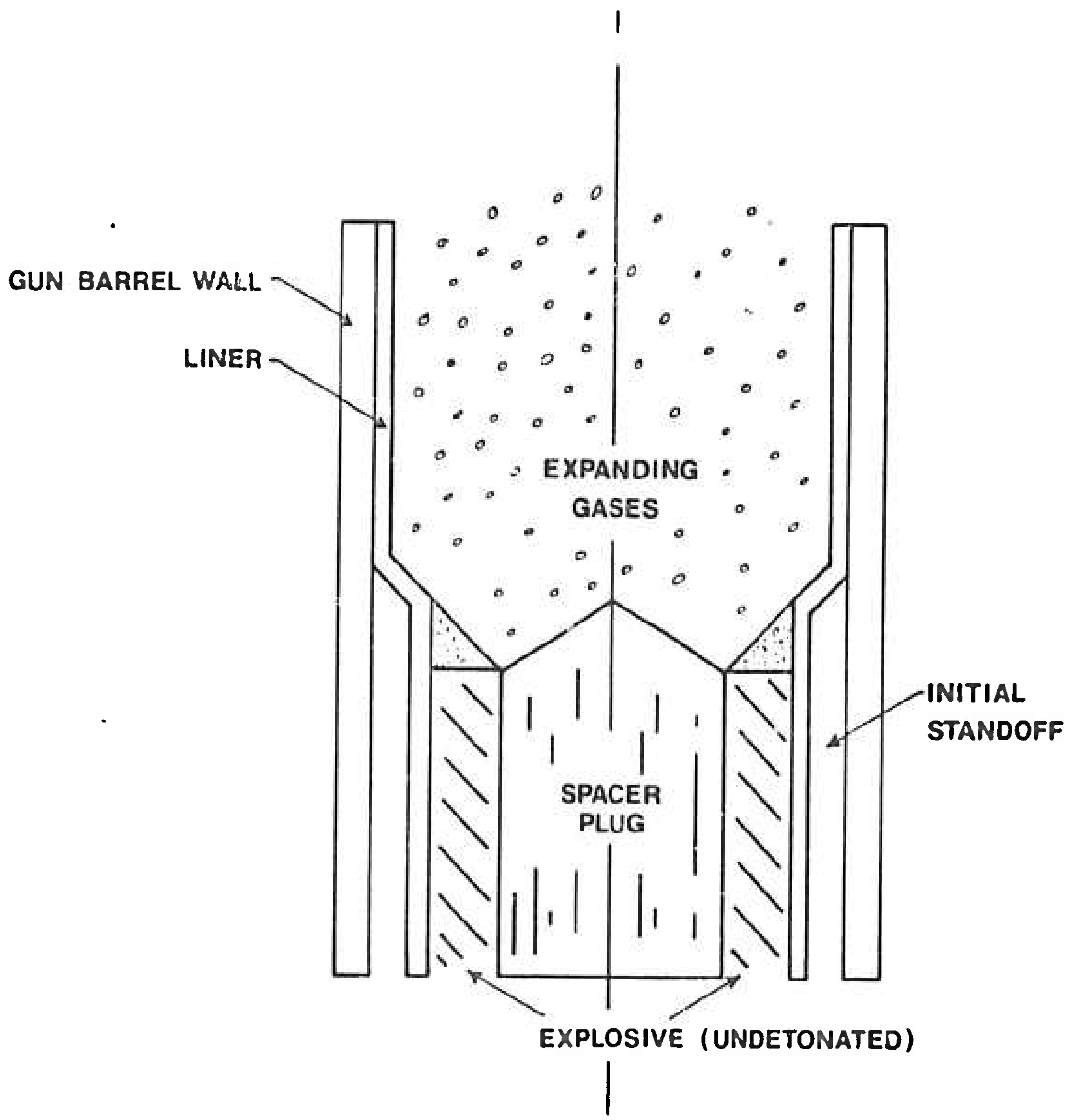
CLADDING RANGE FOR FLAT PLATE

FIGURE 1



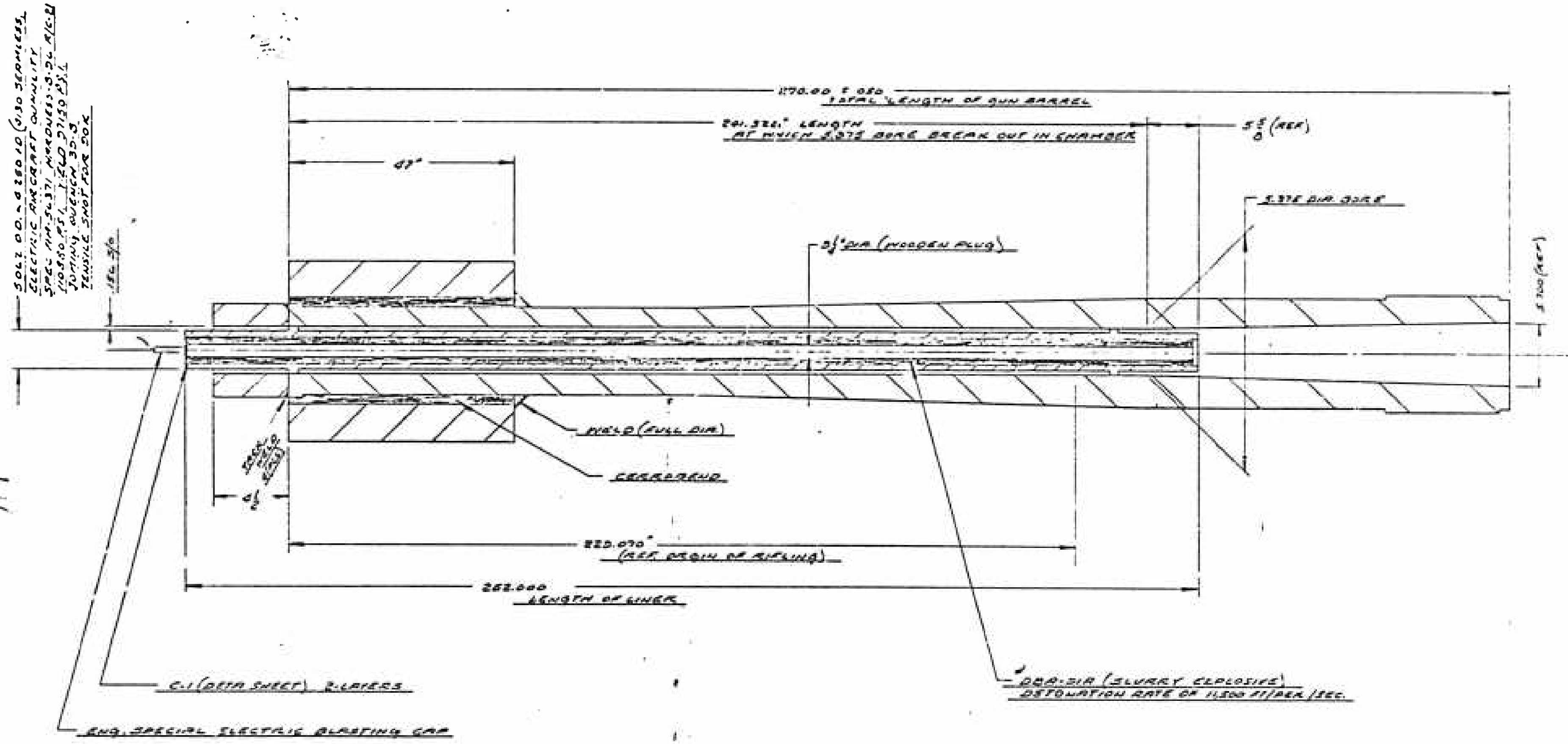
FLAT PLATE CONFIGURATION

FIGURE 2



TUBULAR CLADDING (INNER CASE)

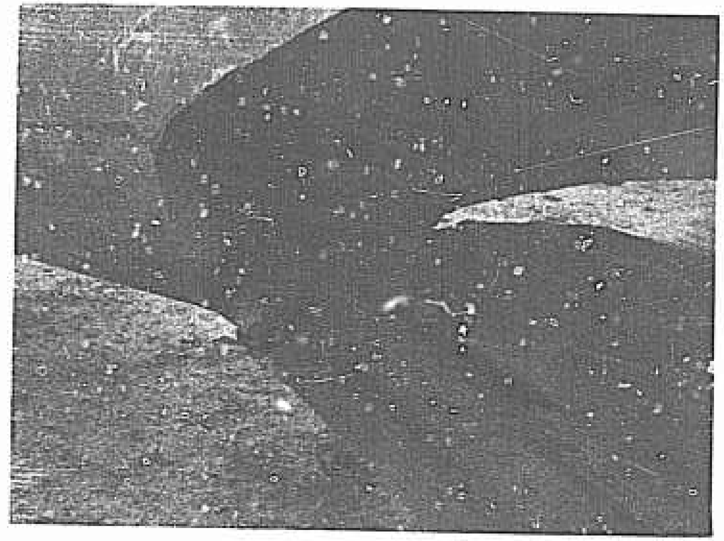
FIGURE 3



CLADDING LINER TO 5"/54 GUN BARREL

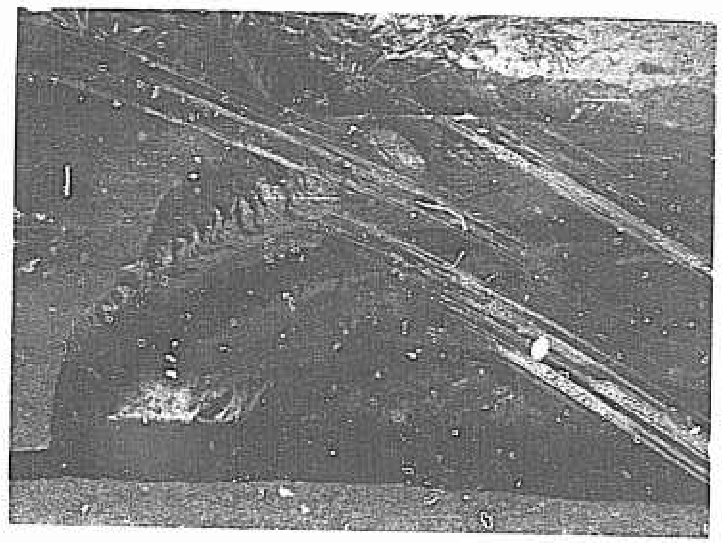
FIGURE 4

A. FIRST TRIAL AT CLADDING



B. RUPTURED 5" GUN BARREL & LINER

C. 5" BARREL & LINER WITH 8" RESTRAINT

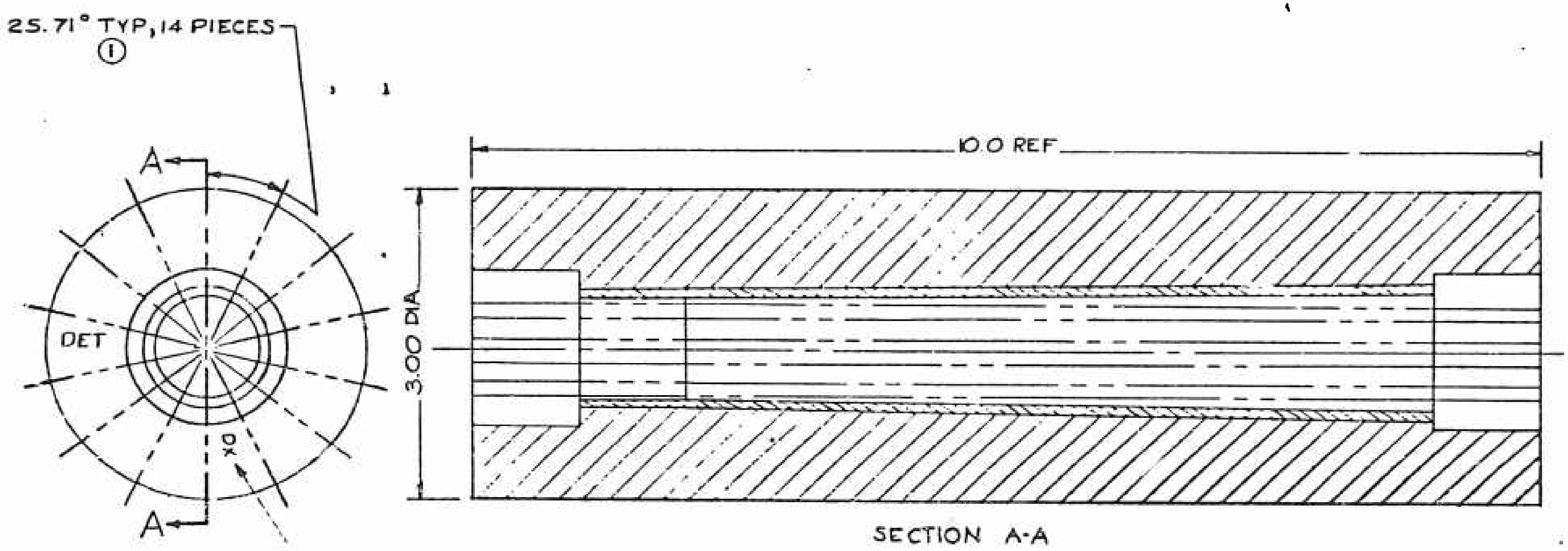


D. 8" RESTRAINT & 5" BARREL

FIGURE 5 TEST SAMPLE [illegible]

NOTES:

1. CUT TUBE LENGTHWISE INTO FOURTEEN EQUAL SEGMENTS AS SHOWN.
2. PRIOR TO SECTIONING, EACH SAMPLE WAS MARKED 'DET' ON ONE END AND STAMPED WITH A NUMBER ON BOTH ENDS. ON EACH OF THE SECTIONS, ON THE END ORIGINALLY MARKED 'DET', STEEL STAMP A 'D' AND THE SAMPLE NUMBER.



SUBSCALE TEST BARREL ASSEMBLY

FIGURE 6

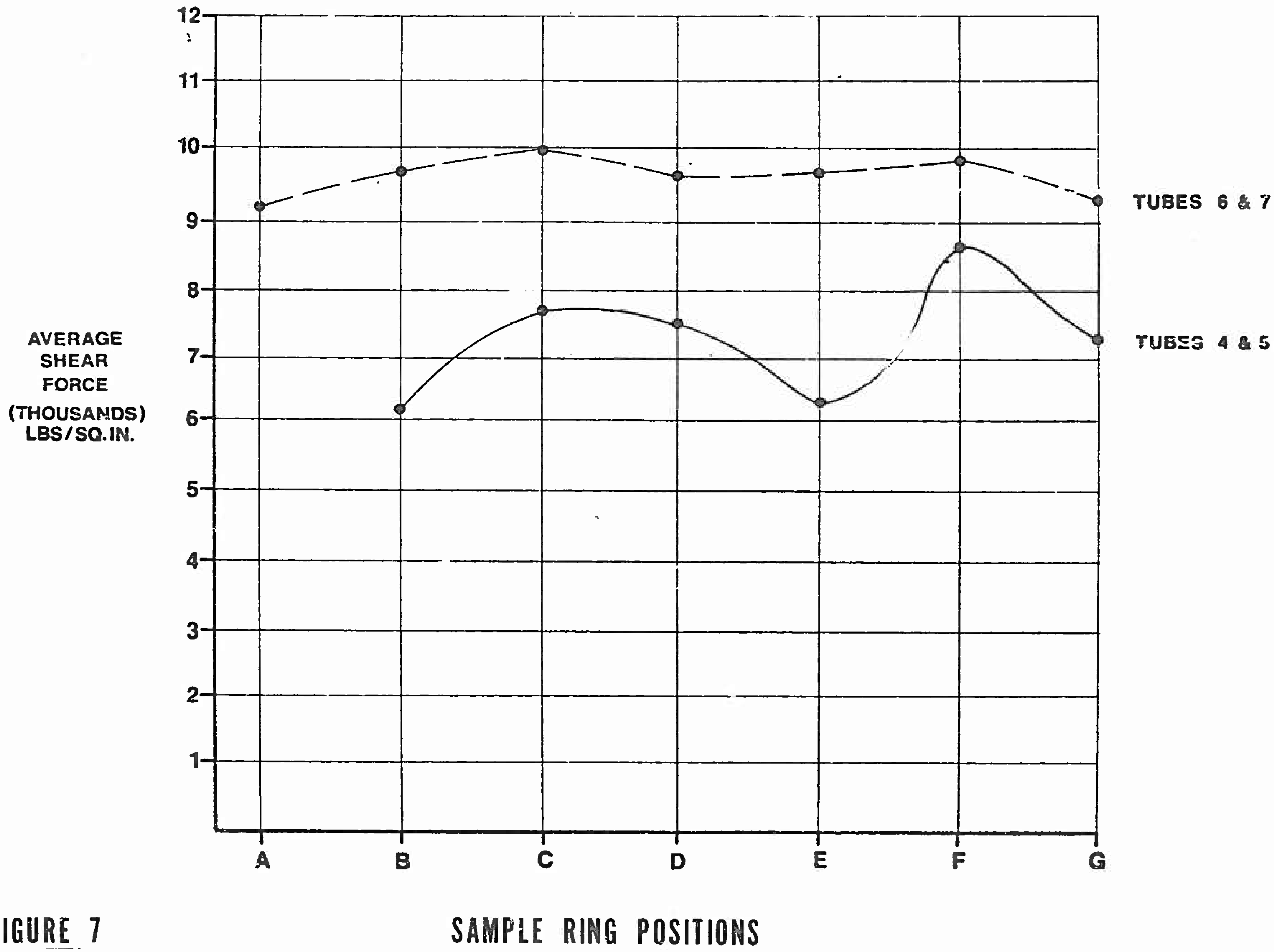

AVERAGE
SHEAR
FORCE
(THOUSANDS)
LBS/SQ.IN.
12
11
10
9
8
7
6
5
4
3
2
1
A
B
C
D
E
F
G
TUBES 6 & 7
TUBES 4 & 5
SAMPLE RING POSITIONS

FIGURE 7

APPENDIX A

EXPLOSIVE CLADDING A 4130 STEEL

LINER TO A 5" GUN BARREL

1. Aerojet-General's statement of work proposal (DP 67M630) for a two-phase program was conducted at China Hills, California.

a. Phase I included shock welding a steel liner into a gun barrel. Phase II provided a training program for Naval Engineering personnel; both phases were performed simultaneously.

2. This program was under the direction of the Advanced Material Technology Department, Aerojet-General Corporation, Downey, California.

a. After developing explosive parameters, a steel liner of AISI 4130 was shock welded into a three foot length of heavy wall gun tube supplied by NOSL. This justified Phase I of the contract. Phase II was performed simultaneously with Phase I and included forty hours of detailed Engineering training in shock welding techniques for four Naval personnel. Twenty percent (20%) of this training was theory and the remainder was directed to practical application.

3. The Advanced Materials Technology Department of Aerojet-General has been actively engaged in research, development, and production in the high energy shock welding field since 1958. The department has explosively welded a variety of similar and dis-similar material types in various sizes and shapes while under a previous Government contract and while engaged in Aerojet's funded research.

STATEMENT OF WORK

PHASE I

Subscale, heavy wall tubing shall be utilized to establish engineering parameters such as explosive load, type and initiation methods. This subscale tubing shall be lined with a steel material AISI 4130 similar to that to be used on the barrel section. This phase will also establish the relation between the 4130 steel liner and the subscale tubing wall to achieve a uniform inner metallic bond. Using these developed parameters a steel liner AISI 4130 will be Shockwelded inside a three (3) foot length of a full scale gun tube.

This gun tube will be supplied by the Navy to the following dimensions:

- Length = 3 foot
- Inside Diameter = 5.375 $\pm$ .010 inches
- Wall Thickness = 3 Inches, approximately

Both the gun tube and the liner will be in the annealed condition prior to welding.

The liner will be furnished by Aerojet. Aerojet will also machine the outside diameter of the liner to establish the proper standoff. The inside diameter will be left as welded.

The samples and barrel section shall be returned to the Naval Ordnance Station, Louisville, Kentucky, for final machining, heat treating, and evaluation within one month after receipt of an order and material.

LINING OF A 5" GUN BARREL BY EXPLOSIVE WELDING

(a) Gun Barrel

The test conditions to which the test program has been planned are essentially the following:

Gun barrel is not heat treated, the liner material to be non-heat treated 4130 steel. Liner material holds 21 to 22 R_C, equivalent to 103,200 psi tensile strength.

Hardness tests on gun barrel, supplied by NOS, give 13.7 R_C, as average of 13 tests, equivalent to 95,400 psi tensile strength. Gun barrel to be machined smooth to 5.375-in. ID, subsequently modified to smooth bore on 26-in. length, followed by a 2-1/8-in. long tapered transition belt and a 7-7/8-in. long unmachined area where the riflings are left intact. Tests to be conducted on the assumption that no outside tooling is required to prevent permanent expansion of gun barrel. Gun barrel and barrel with liner to be A- or C-scanned before and after welding.

(b) Principal dimensions of that part of the liner which goes into the smooth bore are:

5.050-in. OD

4.500-in. ID

These dimensions provide a standoff of 0.163-in. (see Figures 1&2 barrel with liner). Assuming no permanent expansion of barrel, the terminal ID of liner is calculated as follows:

Area:

$$\frac{\pi}{4}(5.050^2 - 4.500^2) = 0.785 \cdot (25.503 - 20.250)$$

$$= 0.785 \cdot 5.253$$

When expanded to 5.375-in., OD and X ID:

$$\frac{\pi}{4}(5.375^2 - X^2) = 0.785 \cdot (28.891 - X^2)$$

$$= 0.785 \cdot 5.253$$

$$X^2 = 28.891 - 5.253 = 23.638$$

$$X = 4.862\text{-in., calculated}$$

which leaves a machining allowance on the side of

1/2 (5.000 - 4.862) = 0.069-in.

It was stipulated at that time that a machining allowance of 1/16-in. = 0.063-in. should be provided. This requirement has later been changed to 1/8-in., but after liner was machined.

It was desired to avoid substantial welding of liner to the rifling, but also to see if such welding would occur. Therefore, the lower 6-in. of the liner was machined to 4.950-in. OD, to center in the barrel with a loose fit, leaving a standoff of only 0.025-in. which was supposed to be insufficient for welding. The next 2 - 1/8-in. was machined to a substantial standoff. This cuts into the wall thickness, and a compromise was made with 0.125-in. standoff and .25-in. wall thickness, resulting in an OD of 4.750-in.

Finally, over the tapered transition area the liner is also taper

turned and the standoff increases linearly from 0.125-in. to 0.163-in.

(c) Subscale Tests

Four (4) subscale tests were made. Material was annealed 4130 steel, outer tube measured 6.50-in. OD and 5.375-in. ID. Inner tube wall thickness and standoff are listed in Table 1. Variations are within prescribed machine shop tolerances. The following observations and conclusions were made:

1-1/2-in. die wall thickness is insufficient against rupture; 3-1/2-in. die wall thickness is sufficient against rupture.

Cerrobend extrudes partly at ends, resulting in hour-glass type deformation of outer tube (greater expansion at ends). Concrete in 6-in. thickness is insufficient to act by its inertia (it is obviously insufficient by its tensile strength).

Explosive charge of 75 gm per inch increments did not weld. Lower limit for charge is apparently around 100 gm per inch increment.

The high-density explosive (20.2 gm/in.^{3} in Test #3) produced local pits. Apparently it produces irregularity in the propagation of the detonation wave.

(d) Test #5, Full Scale Test

Concrete was selected because it is not ductile like Cerrobend, and was confined within a 21-3/8-in. ID stainless steel cylinder

with 1-3/16-in. wall. Heavy steel flanges were provided on ends, Figure 3. . Charge was 103 gm per inch increment. The welding was evaluated by an A-scan (Figure 4). The lack of welding at the upper end is caused by too short a lead to build up stable detonation. This will be corrected.

Pits on the inner surface indicates some disturbance in the detonation. This is presumably caused by instability in the cardboard tube that serves as the inner core for the explosion charge. A test is under preparation where the inner core is made from an aluminum tube welded to the end flange.

The assembly was measured after the welding. There was a slight axial shift in the position of the liner, only 0.129-in. down at the upper end and 0.057-in. down at the lower end, resulting in a shortening of the liner of 0.072-in. or 0.2% which is insignificant as far as diameters are concerned.

O.D.'s on barrel are as follows:

Location	Before (in.)	After			Expansion (in.)
		D_1	D_2	Ave.	
Upper end	9.236	9.284	9.291	9.288	0.052
Middle	9.233	9.336	9.341	9.339	0.106
Lower (rifled) end	9.230	9.278	9.270	9.274	0.044

It is seen that the pattern of expansion is reversed; maximum expandion occurs at the middle. It is the expansion that absorbs a part of, or all of, the planned machining allowance, as shown

by the following calculations:

Upper end:

Area: $\frac{\pi}{4}(9.236^2 - 5.375^2) = 0.785 \cdot (85.304 - 28.891)$

$= 0.785 \cdot 56.413$

When expanded to 9.288-in. OD and X ID:

$\frac{\pi}{4}(9.288^2 - X^2) = 0.785 \cdot (86.267 - X^2)$

$= 0.785 \cdot 56.413$

$X^2 = 86.267 - 56.413 = 29.854$

X = 5.464-in. ID in barrel.

When liner is expanded, not to 5.375-in., but to

5.464-in., OD and Y ID, we get

$Y^2 = 29.854 - 5.253 = 24.601$

Y = 4.960-in., ID of liner,

leaving a machining allowance of

1/2 (5.00 - 4.960) = 0.020-in.

Thus, we have lost 0.069-0.020 = 0.049-in., of

the original machining allowance.

Middle section:

Area:

$\frac{\pi}{4}(9.233^2 - 5.375^2) = 0.785 \cdot (85.248 - 28.891)$

$= 0.785 \cdot 56.357$

Middle section (Cont'd)

When expanded to 9.339-in. OD and Z ID:

$$\frac{\pi}{4}(9.339^2 - Z^2) = 0.785 \cdot (87.217 - Z^2)$$

$$= 0.785 \cdot 56.357$$

$$Z^2 = 87.217 - 56.357 = 30.860$$

$Z = 5.555$-in., ID in barrel.

When liner is expanded, not to 5.375-in., but to 5.555-in. OD and W ID, we get

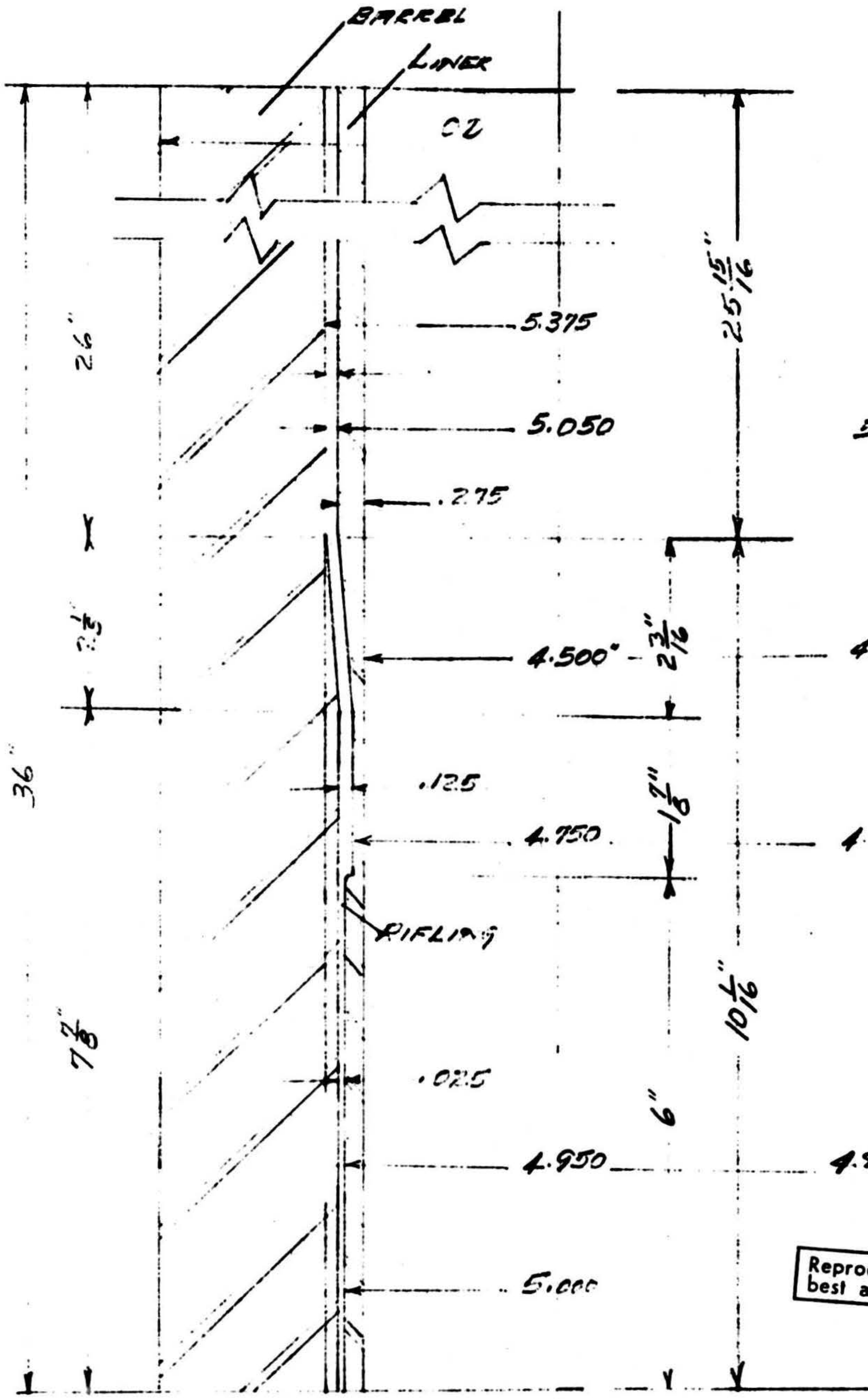
$$W^2 = 30.860 - 5.253 = 25.607$$

$W = 5.060$-in., ID of liner

leaving no machining allowance, but an oversize of 0.060-in., or approx. 1/16 - in., on the diameter.

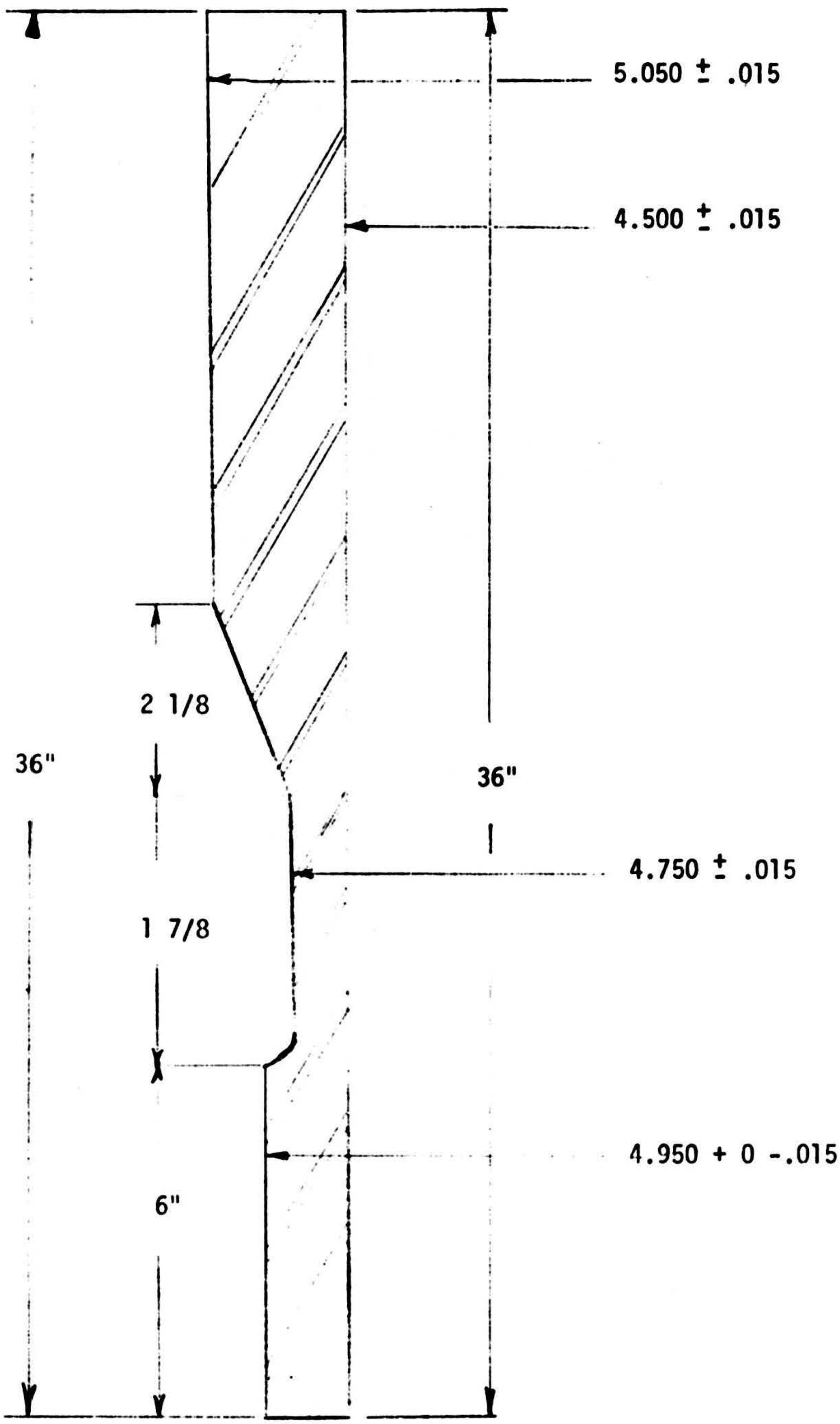
These deviations can be taken care of by a corresponding increase in the wall thickness of the liner, but should be eliminated when expansion is reduced or prevented by better support or higher strength barrel.

TEST NO.	WALL THICKNESS (IN.)	STANDOFF (IN.)	CONFINEMENT	EXPANSION OF TOP, MIDDLE & BOTTOM DIAMETERS (IN.)
1	0.269	0.169	Cerrobend, Alum. End Rings Steel Die, 1-1/2 + 2 in. wall.	0.288-0.108-0.244 1-1/2-in. die wall fractured.
2	0.278	0.161	Cerrobend, Alum. End Rings Steel Die, 6-in. Wall.	0.103-0.055-0.085 Cerrobend extruded.
3	0.269	0.169	Cerrobend, heavy Alum. End Flanges, Steel Die, 6-in. Wall.	0.091-0.067-0.166 Cerrobend extruded.
4	0.269	0.169	Concrete, 8-in. Thick in Drum.	Tube and concrete split.



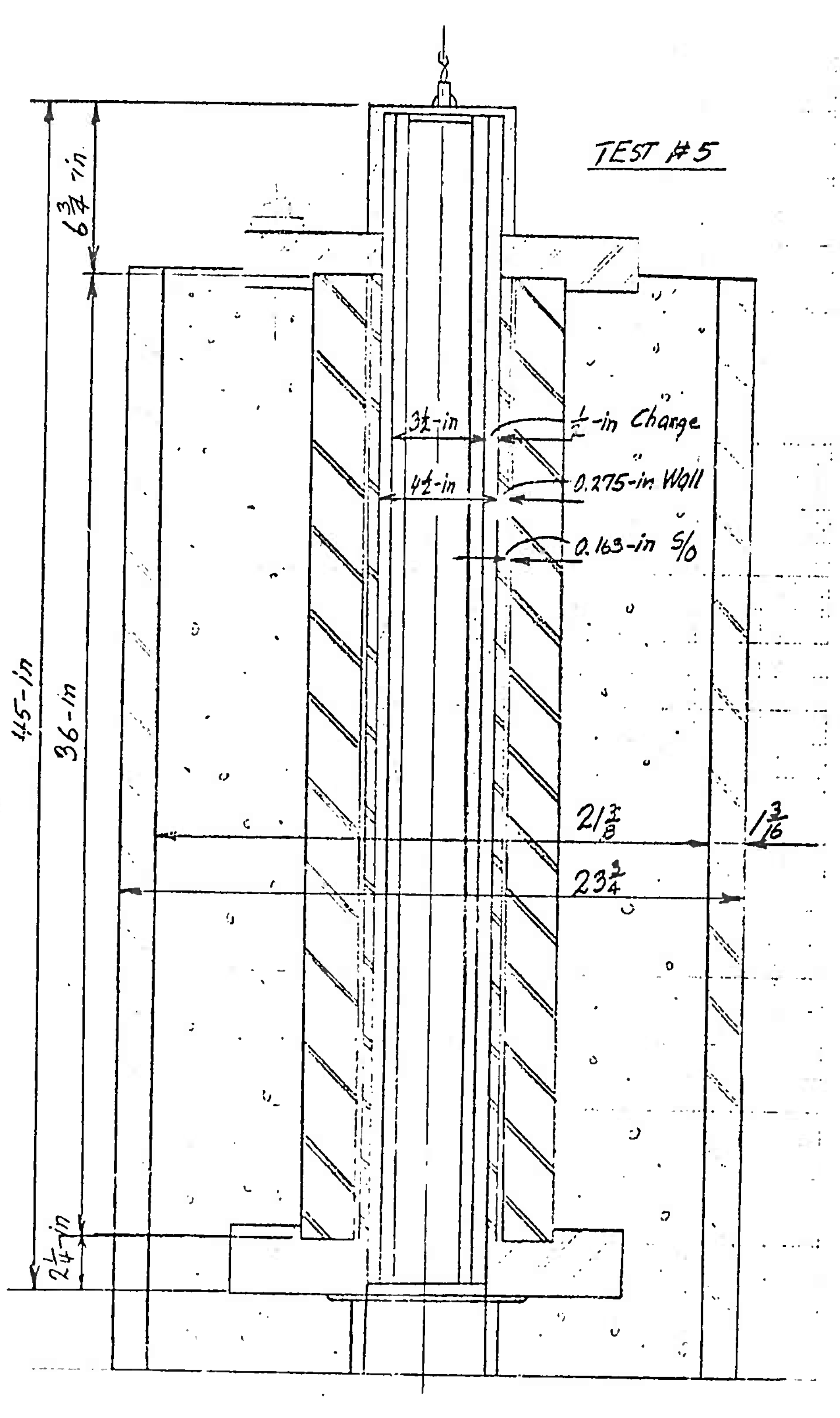
SKETCH OF BARREL AND LINER

FIGURE 1



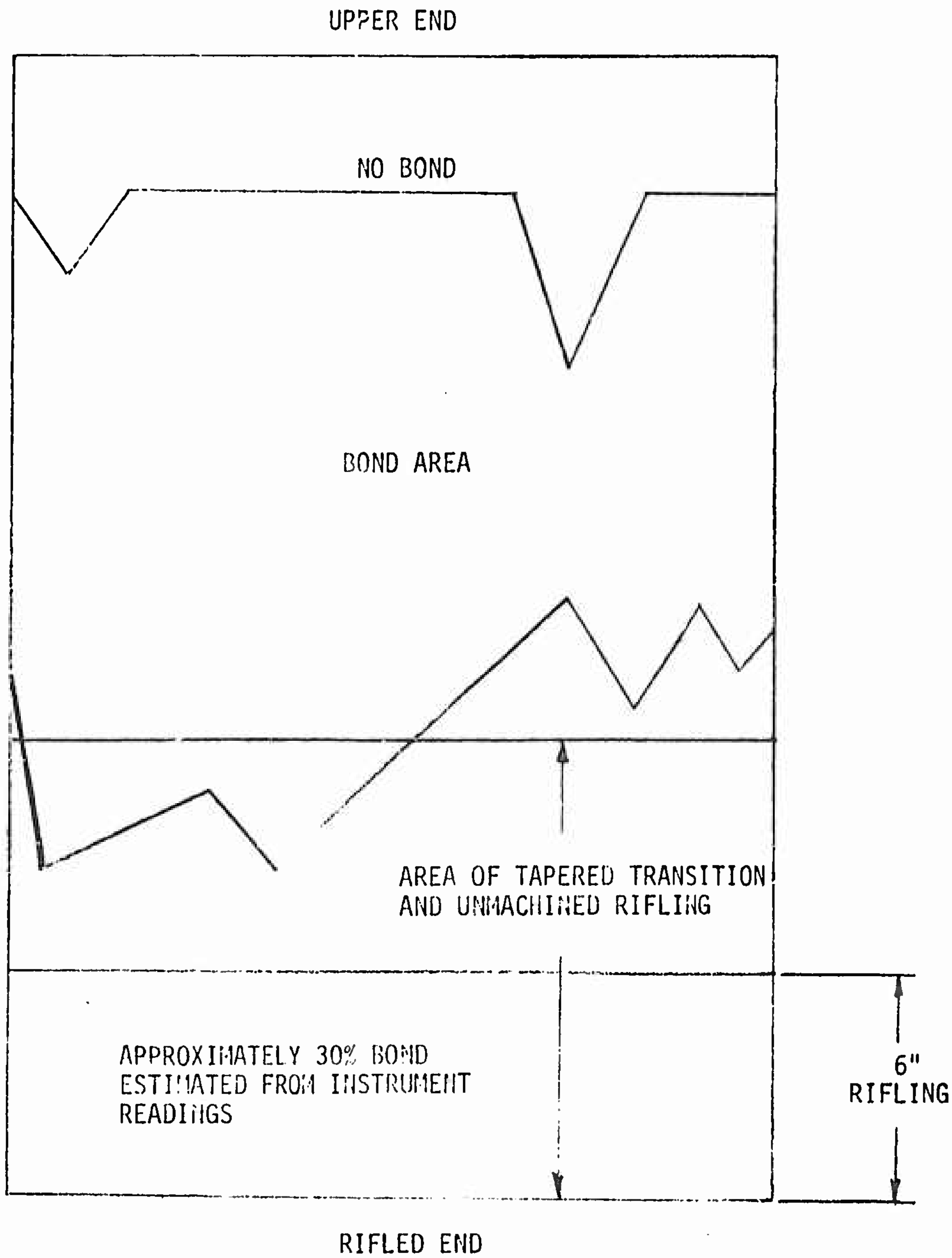
ENLARGED SECTION OF FIGURE 1

FIGURE 2



FULL SCALE TEST SAMPLE

FIGURE 3



3 FT. GUN BARREL A-SCAN TEST #5

FIGURE 4

APPENDIX B

EXPLOSIVE CLADDING A 4130 STEEL

LINER TO A 5" GUN BARREL

1. Aerojet-General's statement of work proposal for a consecutively four-phase program conducted at China Hills, California.

a. Phase I - Explosively cladding a steel liner into a 36" section of hardened 30 to 40 Rockwell "C" gun barrel.

b. Phase II - The evaluation of Phase I and explosively cladding a short section (approximately 3 feet long) of steel liner to the inner walls of a full length 5 inch I.D. gun barrel. The area selected for cladding was just forward of the breech.

c. Phase III - Evaluate and establish the necessary standards for non-destructive testing techniques used in determining the percentage of bond on gun barrel liners.

d. Phase IV - The evaluation of candidate materials to be used as possible bonding liners and the investigation of explosively cladding materials such as titanium, cobalt base alloy, and various high-strength steels.

NOTE: Due to limited funds, only Phases I and II were conducted.

AEROJET-GENERAL CORPORATION
ORDNANCE DIVISION
601 South Placentia Avenue
Fullerton, California 92631

EXPLOSIVELY CLAD GUN BARREL AND EVALUATE NON-DESTRUCTIVE TESTING TECHNIQUES

NAVAL ORDNANCE STATION
LOUISVILLE, KENTUCKY

Final Report - 3443-01 (F)

27 June 1969 to 31 January 1970

Contract N00197-68-C-0712

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Classification - Unclassified

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COPY NO. 8

CONTENTS

STATEMENT OF WORK

Phase I

The Naval Ordnance Station, Louisville, Kentucky, shall furnish f.o.b., Aerojet-General Corporation's Chino Hills, California facility one short gun barrel section not to exceed 36" in length which has been pre-bored to a "to be determined" dimension. This section shall have a hardness of approximately 30 to 40 on the Rockwell "C" range. Aerojet will then supply the necessary services and additional material to explosively clad a liner of a type of steel similar to the gun to the inner walls of the barrel to approximate the original size of the barrel. This effort will include determination of the necessary parameters such as explosive load, standoff distances and method of initiation to be used. After completion of the cladding, the barrel section will be subjected to a non-destructive test to evaluate the percentage of bond. This barrel shall then be returned f.o.b., the Chino Hills facility, along with the test data obtained, to the Naval Ordnance Station, Louisville, for further evaluation.

This phase will be completed in eight (8) weeks after receipt of an order and the Navy-furnished barrel section. Return of the barrel with the liner added and the test data to the Naval Ordnance Station will be the basis for acceptance and payment for Phase I.

Phase II

After receipt of the Phase I barrel section, the Naval Ordnance Station shall furnish Aerojet f.o.b., Chino Hills, a full-length 5" gun barrel pre-bored to a "to be determined" dimension and also having a Rockwell "C" hardness of approximately 30 to 40. Utilizing the parameters established in Phase I, Aerojet shall explosively clad a steel liner to the area just forward of the breech to approximate the original size of the barrel. This liner will be approximately three (3) feet long and of a steel similar to the gun barrel.

After explosively cladding this liner to the inner walls of the full-length gun barrel, the barrel shall also be subjected to a non-destructive test as in Phase I, and returned f.o.b., Chino Hills, to the Naval Ordnance Station, Louisville, with the test data. If support tooling is required for cladding this barrel, the Naval Ordnance Station shall provide to Aerojet without charge a scrap barrel contoured to an inside dimension adequate to accept the 5" barrel.

Phase II will be completed within eight (8) weeks after customer notice to proceed and receipt of Navy-furnished materials. Return of the barrel with the liner added and test data to the Naval Ordnance Station will be the basis for acceptance and payment for Phase II.

Phase III

Aerojet shall supply the necessary services and materials to evaluate the various methods and types of non-destructive testing available for determining the bond condition of explosively clad gun barrel components. During this phase, necessary standards to be used in non-destructive testing to permit determination of the percentage of bond for short and full size barrel sections will be established. Subscale, heavy wall steel sections shall be clad, C-scanned or A-scanned and then sectioned to prove that the printed readout of the subscale standard coincides with the actual bond condition.

Receipt by the Naval Ordnance Station of the test data and Aerojet's report of its findings and recommendations for non-destructive testing standards will be the basis for acceptance and payment for Phase III. This phase will be completed within nine (9) weeks after customer notice to proceed.

Phase IV

The purpose of Phase IV will be the evaluation of other materials to be used as possible liners for prolonging the life of gun barrels. Aerojet intends to evaluate the following five (5) types of material candidates for gun barrel liners:

(1) 90-10 tantalum 0.020" thick, to be wrapped over, and welded on to existing (but oversize) riflings in a gun barrel section.

Phase IV (Cont'd)

(2) 90-10 tantalum 5/16" thick, to be welded into a prebored gun barrel.

(3) H-11 steel, to be welded as in (2), above.

(4) Maraging steel, to be welded as in (2), above.

(5) A cobalt base, high-chromium alloy, to be welded as in (2), above.

In the performance of this phase, Aerojet reserves the right to substitute other materials for those recommended above.

Naval Ordnance Station shall furnish to Aerojet, F.O.B., Chino Hills, six (6) each gun barrel sections not to exceed 12" in length for this effort. One of the sections shall have oversize riflings and the other five shall be prebored. Before conducting the intended program, one of the prebored sections shall be tested without a cladding to provide control data for hardness and wear tests. Upon receipt of the sections by Aerojet, the necessary engineering parameters needed for the explosive cladding of the dissimilar materials to the inner walls will be calculated. After the explosive cladding operation each of the five sections with liners shall be non-destructively tested to determine effectiveness and percentage of the dissimilar material bond.

These short sections will then be shipped F.O.B., Chino Hills, to the Naval Ordnance Station along with the test data for further evaluation. The receipt by the Naval Ordnance Station of the five lined sections and test data will be the basis for acceptance and payment for Phase IV. This Phase will be completed in nine (9) weeks after receipt of the customer's notice to proceed and the six (6) short gun barrel sections.

The tooling investigated consisted of steel tubing which had a loose sliding fit over the O.D. of the gun barrel. The annulus between the I.D. of the steel tube and the O.D. of the gun barrel was filled with either concrete or Cerro-bend metal thereby making the assembly rigid.

4. PREVIOUS EXPERIENCE

4.1 Previous Testing

AGC was authorized by the Naval Ordnance Station to conduct investigations into the feasibility of explosively cladding steel liners in the I.D. of five-inch gun barrels. These studies proved conclusively that explosive cladding procedures were feasible in this case. Certain parameters, however, remained obscure. The pertinent information extracted from the previous investigation was in regard to the following explosive cladding parameters:

- o The stand-off dimension which is described as the annulus measured radially between the I.D. of the gun barrel and the O.D. of the steel liner.
- o Explosive charge physical properties.
- o Tooling material and configuration.
- o Quality of the bond obtained at the clad interface.
- o Permanent deformation produced in both the gun barrel and the tooling as a result of the explosive cladding procedure.

4.1.1 Stand-Off Dimension:

The stand-off dimension is an important process parameter included in explosive welding specifications. This dimension controls, in part, the impact velocity generated at the bond interface during the explosive welding procedure. The stand-off dimension is the measurement of the space between the I.D. of the gun barrel and the O.D. of the steel liner. The pertinent parameters tested thus far, in this regard, are reported in Table 1. (See Page No. 3.)

4.1.2 Explosives:

The explosives investigated during the preceding authorization were constructed from Trojan Dynamite Grade GL-70. For all tests the explosive charge was tubular in shape and was placed internally in the I.D. of the steel liner with the O.D. of the explosive charge in contact with the I.D. of the steel liner.

The dimensional measurements and the loading properties of the explosive charges are shown in Table II.

TABLE I
SPECIFICATIONS RELATED TO STAND-OFF DISTANCE
GUN BARRELS AND STEEL LINERS RECORDED IN INCHES

Sample No.	Stand-Off	Gun Barrel		Steel Liner		
		O.D.	I.D.	O.D.	I.D.	Wall
1	0.169	6.50	5.375	5.037	4.50	0.269
2	0.161	6.50	5.375	5.055	4.50	0.278
3	0.169	6.50	5.375	5.037	4.50	0.269
4	0.169	6.50	5.375	5.037	4.50	0.269
5	0.163	9.233	5.375	5.050	4.50	0.275

TABLE II
EXPLOSIVE CHARGE SPECIFICATIONS FOR
TROJAN DYNAMITE GRADE GL-70

Sample No.	Density Grams/ Cu.In.	Amount		Dimensions in Inches			
		Grams/ Sq.In.	Grams	O.D.	I.D.	Wall	Length
1	16.4	8.85	1500	4.50	3.25	0.63	12.0
2	16.4	7.28	618	4.50	3.50	0.50	6.0
3	19.9	6.82	1450	4.50	3.75	0.38	15.0
4	16.4	8.01	1966	4.50	3.33	0.59	16.5
5	16.4	7.3	4635	4.50	3.50	0.50	45.0

4.1.3 Tooling:

The tooling utilized to support the O.D. of the gun barrel during the explosive welding procedures was made from steel tubing and either concrete filler material or Cerro-bend metal filler material. One test, Test No. One, was conducted utilizing concrete filler material while the remaining four tests were conducted utilizing Cerro-bend metal filler material.

4.2 Results of Test Conducted Previously

4.2.1 General Observations:

Evidence of a bond between the steel liner and the gun barrel was found as a

result of several tests. The results of these findings will be discussed in the following Paragraph 4.2.2.

The tooling utilized thus far, yielded pertinent information which was used to establish tooling criteria for the current authorization. The finding of the tooling investigation is described in Paragraph 4.2.3.

4.2.2 Explosive Bond Quality:

The results of the tests conducted thus far were examined and the following conditions were found as far as the bond between the steel liners and the gun barrels is concerned.

- o Test No. 1 - Large areas were found to be bonded. Those sections which were found to contain unbonded areas were attributed to the improper method with which the main explosive charge was initially detonated.

- o Test No. 2 - This sample was 12-inches long. The leading 6-inches of the sample was found to contain a bonded area while the latter 6-inches was found in an unbonded condition. The leading end of the sample was tested explosively as shown in Table II while the latter half was tested with an explosive charge having a lesser amount and was also smaller in size. The specifications for the explosive charge utilized for the latter section of this test, was purposely deleted from Table II.

- o Test No. 3 - Since this test was designed to examine tool performance and also gun barrel dimensional stability, the bonds obtained in the samples as a result of the test were not investigated.

- o Test No. 4 - The tooling and the gun barrel failed catastrophically during this test. As a result the sample yielded a very poor bond.

- o Test No. 5 - The I.D. of the gun barrel contained several bore diameters which therefore provided several stand-off dimensions. Bonding was observed only where the stand-off distance measured 0.163-inches as reported in Table I.

4.2.3 Measurements of Tooling and Gun Barrels Before and After Testing:

The O.D. of the tooling and the O.D. of the gun barrel was measured diametrically before testing and comparisons were made with measurements made at the same point after testing. The results of these findings are listed in Table III.

TABLE III
AVERAGE DIAMETRIC DIMENSIONS OF TOOLING AND GUN BARRELS BEFORE AND AFTER TESTING

Test No.	Tooling O.D. In Inches			Gun Barrel O.D. In Inches		
	Before	After	Expansion	Before	After	Expansion
1	10.333	10.466	0.133	6.500	6.695	0.195
2	21.025	Same	Nil	6.500	6.565	0.065
3	21.025	Same	Nil	6.500	6.596	0.096
4	---	---	Failed	---	---	Failed
5	23.750	---	---	9.233	9.300	0.067

The amount of permanent deformation which was measured in terms of expansion, revealed that Test No. 2 and Test No. 5 yielded the least amount of diametric change 0.065-inch and 0.067-inch respectively.

4.2.4 Conclusions Drawn from Previous Test:

Summarizing the results of the investigation conducted thus far, the following conclusions were drawn:

- Bonding of the steel liner to the gun barrel was accomplished in Test No. 2 and Test No. 3.

- The pertinent parameters which were utilized for these two tests are shown in Table IV and are extracted from Table I, II, and III.

TABLE IV
PERTINENT PARAMETERS DRAWN FROM TABLE I, II, and III

Test No.	Stand-Off In Inches	Liner Wall Thickness In Inches	Explosive Charge		Gun Barrel O.D. Expansion In Inches
			Amount Grams/ Sq. In.	Wall Thickness In Inches	
2	0.161	0.278	7.28	0.50	0.065
5	0.163	0.275	7.3	0.50	0.067

- The explosive welding parameters listed above will, in all probability, produce effective bonds between steel liners and gun barrels.

- Insufficient empirical data has been obtained thus far in order to make a projection at this time, as to the shape or the type of material to be utilized for tool fabrication.

5. WORK PERFORMED

5.1 General

In all, four gun barrel sections were explosively clad internally with steel liners. Of the four barrel sections, three were tested to develop the explosive cladding process parameters while the fourth gun barrel section, being longer by a factor of three, was tested to evaluate the process parameter developed thus far. The gun barrels were dimensionally inspected before and after each test to determine if any resultant diametric change had occurred.

Ultrasonic inspection techniques were investigated as a possible method for non-destructively examining the integrity of the bond achieved between the steel liner and the gun barrel.

5.2 Material

5.2.1 Five-Inch Gun Barrel:

The gun barrel material utilized during this investigation was furnished by the U. S. Naval Ordnance Station, Louisville, Kentucky. A five-inch gun barrel, which was worn in service, was selected by the Naval Ordnance Station and divided into short sections and subsequently bored in the I.D. to remove the worn surface. These gun barrel sections were prepared in such a manner so that a steel liner could be explosively bonded in the I.D. thereby providing new material in order to restore the original bore. Four gun barrel sections ranging from 11.38-inches long to 11.94-inches long, and one gun barrel section measuring 37.83-inches long were tested. One gun barrel section, Sample No. 9, was utilized for material examination only and was therefore not tested explosively. The gun barrel sections as supplied by the Naval Ordnance Station are dimensionally described in Table V.

TABLE V
SPECIFICATIONS OF GUN BARREL
SECTIONS AS SUPPLIED BY THE NAVAL ORDNANCE STATION

Sample No.	Dimensions in Inches			
	Length	I.D.	O.D.	Wall
6	11.563	5.385	7.339	0.977
7	11.938	5.380	7.675	1.148
8	11.688	5.354	8.093	1.370
9	11.375	5.368	10,131	2.382
10	37.83	5.353	12.673	3.660

5.2.2 Steel Liners:

The steel liners tested during this period were made from AISI 4130 seamless steel tubing, heat treated to Rockwell Hardnesses ranging from R_c27 to R_c32. The raw steel tube purchased for the first test in this series measured 4.50-inch O.D. by 3.87-inch I.D. by 0.313-inch wall, while the remaining three steel tubes measured 5.25-inch O.D. by 4.50-inch I.D. by 0.38 wall. Subsequent to heat treating, the steel tubes were machined to conform to the specifications, as listed in Table VI. Since gun barrel Sample No. 9 was not tested explosively, no steel liner was provided.

TABLE VI
STEEL LINER DIMENSIONAL SPECIFICATION

Sample No.	Dimensions In Inches			
	Length	O.D.	I.D.	Wall
6	20.00	4.504	3.860	0.322
7	13.00	5.000	4.500	0.250
8	12.70	5.000	4.500	0.250
10	37.830	5.000	4.500	0.250

5.2.3 Tooling:

Dies were constructed from steel tubing in order to support the O.D. of the gun barrel during the explosive welding procedure. The I.D. of the steel die was a loose fit over the O.D. of the gun barrel. The assembly was made rigid by filling the annulus between the O.D. of the gun barrel and the I.D. of the steel die with either concrete or Cerro-bend metal. For the first test, concrete was utilized as the filler material while for the remaining tests, Cerro-bend metal was utilized as the filler material. The wall thickness of the annulus filler material varied from test to test because of two conditions:

1) Three steel dies were tested each having dimensions which were not constant.

2) The normal O.D. of a gun barrel is tapered and therefore each gun barrel section had varying O.D. dimensions. The description of the die material and their respective dimensions are listed in Table VII. The O.D. of the gun barrels are reported as an average O.D. See Page No. 8.

TABLE VII
DIE MATERIALS AND DIMENSIONS

Sample Number	Tooling Specifications				Annulus Filler Specification			
	Material	Dimensions In Inches			Material	Dimensions In Inches		
	Type	O.D.	I.D.	Wall	Type	O.D.	I.D.	Wall
6	C-1015 Hot Finished Steel	11.982	7.500	2.241	Burks Cement	7.50	7.339	.081
7	AISI 4130 Steel	12.840	8.840	2.000	Cerro-Bend Metal	8.840	7.675	.583
8	AISI 4130 Steel	12.840	8.840	2.000	Cerro-Bend Metal	8.840	8.093	.374
10	SCH 140 Steel Pipe	16.000	13.125	1.438	Cerro-Bend Metal	13.125	12.673	.226

5.3 Explosive Charges:

The main explosive charges which were tested were made from Trojan Dynamite grade GL-70. The dynamite was tested at 16.4 grams/cu.in. density for the first test, while for the remaining three tests the explosive charge was tested at 20 grams/cu.in. density. The explosive main charges were tubular in shape and were inserted in the I.D. of the steel liner. These explosive charges were detonated at one end utilizing plain wave generators constructed from Detasheet explosive PETN, Grade C-1.

For the first test a wooden dowel having 2.825-inch diameter at one end and 3.045-inch diameter at the other end, was utilized for the core material around which the main explosive charge was constructed. In so doing, an explosive charge was tested which consisted of two individual wall thicknesses. For this explosive charge, and for all the subsequent explosive charges the O.D. was uniform since they were all confined by the I.D. of the steel liners.

The three remaining tests were conducted utilizing explosive charges with uniform wall thicknesses. For these explosive charges thin walled aluminum tubing was utilized for the core material around which the main explosive charge was constructed. In all cases, the main explosive charge was constructed with a dimension longer than the relative gun barrel. This increase in length was utilized at the detonating end of the explosive to allow for explosive detonation pressure wave stabilization. The specifications for the explosive charges investigated are listed in Table VIII.

TABLE VIII
MAIN EXPLOSIVE CHARGE SPECIFICATIONS
FOR TROJAN DYNAMITE GRADE GL-70

Sample No.	Amount in Grams	Dimensions in Inches			
		O.D.	I.D.	Wall	Length
6	1330	3.859	2.825	0.517	14
	450	3.859	3.045	0.407	6
7	2430	4.50	3.00	0.75	13.75
8	2256	4.50	3.00	0.75	13.45
10	6891	4.50	3.00	0.75	39

The explosive charges were constructed in such a manner so as to insure uniform packing density throughout the structure. This was accomplished by measuring individually, the amount of explosive required for each one-inch of incremental length. The measured increment of explosive was inserted into the test

arrangement and pressed to a measured stop. This insertion of the explosive was continued until the total calculated amount of explosive was in place.

5.4 Stand-Off Dimension:

The stand-off dimensions investigated during the previous authorization, which are reported previously in Table IV, indicate that the explosive bonding may be achieved when the stand-off dimension between the steel liner and the gun barrel is 0.162-inches. Assuming that 0.162-inch stand-off dimension may be marginal, it was decided to increase the stand-off distance to 0.441-inch for the first test conducted during the current authorization. This large stand-off distance proved to be excessive. For the succeeding tests, the stand-off distance investigated ranged from 0.177-inch to 0.190-inch. These stand-off dimensions are shown in Table IX together with the steel liner O.D. and the gun barrel I.D.

TABLE IX
DIMENSIONS OF STAND-OFF DISTANCE,
STEEL LINER O.D. AND GUN BARREL I.D.

Sample No.	Measurement In Inches		
	Stand-Off	Liner O.D.	Gun Barrel I.D.
6	0.441	4.504	5.385
7	0.190	5.000	5.380
8	0.177	5.000	5.354
9	N/A	N/A	5.368
10	0.177	5.000	5.383

5.5 Test Arrangements:

Two basic test arrangements were utilized for explosively bonding steel liners to the I.D. of gun barrel sections. One test arrangement comprised an explosive charge which was constructed in such a manner so that two explosive charge thicknesses could be investigated individually. Only one test, namely Test No. 6, was conducted utilizing this test arrangement which is shown in Figure No. 1. The remaining test arrangement which is shown in Figure No. 2, comprised an explosive charge which was constructed with thicknesses which were uniform throughout. Test No. 7 and No. 8 and No. 10 utilized the latter test arrangement.

5.5.1 Test No. One:

The initial test conducted in this series of tests was designed to examine the effect of an explosive charge which was constructed so that the thickness of the

explosive charge measured 0.517-inches thick and 0.407-inches thick respectively. In so doing two explosive detonating pressures could be investigated individually. The test arrangement which was utilized in this case is shown in Figure No. 1. The following assembly procedure was utilized and is listed in chronological order.

- o Insert the gun barrel sample concentric within the die cavity, equally spaced from either end with the axial center line of the test arrangement in a vertical position.

- o Fill the annulus between the O.D. of the gun barrel and the I.D. of the Die Cavity with Burks cement and allow to cure for four days.

- o Insert wooden core in the axial center of the bottom plate.

- o Insert unit assembled above concentrically in the axial center of the gun barrel and die assembly.

- o Install the steel liner within the test arrangement making sure that the liner is located securely in the land provided on the bottom plate.

- o Install upper plate making sure that the land provided on the lower face, locates the liner concentric within the I.D. of the gun barrel.

- o A cylinder of Burkes Concrete 12-inch O.D. by 3.86-inch I.D. by 6-inch long is placed concentrically over the upper section of the test arrangement.

- o Measure six equal increments 75 grams of Trojan Dynamite and insert each increment into the test arrangement individually. After each increment of explosive is inserted in the test arrangement, the bulk explosive is pressed to an increment measuring one-inch in length thereby producing an increment of explosive charge having a density measuring 16.4 grams/cu.in. insert six increments of explosive making up the first six-inches of the main explosive charge. The remaining fourteen-inches of the main explosive charge is produced by measuring fourteen increments of Trojan Dynamite weighing 95 grams each. These increments are sequentially inserted into the test arrangement and subsequently pressed to increments measuring one-inch in length as described above.

- o Fabricate a flat wave generator from Deta-Sheet explosive grade C-1. The flat wave generator consists of a disc of sheet explosive measuring 3.8-

inches in diameter and a pellet made from the same explosive material mentioned previously, measuring 1/2 inch long attached to the axial center of the explosive disc utilizing plya bond rubber cement.

- o Place the flat wave generator in contact with the upper end of the main-explosive charge.
- o The entire test arrangement is suspended in air 12-inches above ground, with the axial center in a vertical position.
- o The main explosive charge is detonated with a No. 8 blasting cap firmly attached to the free end of the sheet explosive pellet which is part of the flat wave generator.

5.5.2 Test No. Seven and Test No. Eight:

Test No. Seven and Test No. Eight was conducted with test arrangements as shown in Figure No. 2. These test arrangements were similar in nature to each other but differed with the previous test as follows:

- o For these two tests the explosive charge thickness remained uniform while for the previous test, the explosive charge consisted of two explosive charge thicknesses.
- o Cerro-bend metal was utilized in place of cement for the annulus filler material.
- o A vacuum atmosphere measuring 29-inches of mercury was inserted between the O.D. of the steel liner and the I.D. of the gun barrel in place of an ambient atmosphere.

The following assembly procedures were utilized and are listed chronologically:

- o Insert the gun barrel sample concentric within the die cavity equally spaced from either end with the axial center line of the assembly in a vertical position.
- o Fill the annulus between the O.D. of the gun barrel and the I.D. of the die cavity with Cerro-bend metal.
- o Attach the bottom plate to the gun barrel and secure with permagum thereby providing a vacuum tight seal.
- o Insert the steel liner concentric within the I.D. of the gun barrel and secure to the bottom plate with permagum.

- o Attach the upper plate to the gun barrel making sure that the upper end of the liner is concentrically positioned. Secure this unit with permagum.

- o Install the aluminum core tube in the axial center of the assembly after first securing a steel end cover with vinyl tape.

- o Insert a vacuum hose through the bottom plate and connect to a vacuum pump.

- o Evacuate the annulus between the O.D. of the steel liner and the I.D. of the gun barrel, introducing a vacuum pressure measuring approximately 29-inches of mercury.

- o Insert the Trojan Dynamite in incremental amounts and press to a uniform density.

- o Install a plain wave generator on the upper end of the main explosive charge.

- o Detonate the explosive charge utilizing a No. 8 blasting cap attached to the upper end of the plain wave generator.

5.5.3 Test No. Ten:

Test No. Ten was assembled utilizing the optimum parameter developed during the preceding tests. With the exception that this test was approximately longer by a factor of three compared with the preceding tests all assembly procedures were similar as those assembly procedures described in Paragraph 5.4.2 with the exception of the added length.

5.6 Test Evaluation:

Prior to each test the gun barrel and the associated tooling were dimensionally inspected and the findings were recorded. Any resultant dimensional change which was found, was compared with dimensional inspection findings obtained prior to each test.

Dimensional evaluation of the tooling was also performed by comparing resultant dimensional changes.

The bond obtained between the steel liner and the gun barrel was examined utilizing destructive testing techniques and also non-destructive testing techniques.

One gun barrel section, Sample No. 9, was examined on the I.D. to determine if any stress corrosion fractures were apparent prior to subjecting the sample to explosive bonding procedures. This sample was not, however, subjected to explosive testing. The examination described above was performed utilizing dye penetrant inspection techniques.

6.0 RESULTS OF WORK PERFORMED

Five-inch gun barrel sections which were explosively clad internally with heat treated steel liners were examined to determine the reliability of the explosive bonding procedures developed during this authorization. Explosively lined gun barrel samples were examined, dimensionally, destructively, and ultrasonically.

The tooling developed to support the gun barrel during the explosive welding procedure was investigated dimensionally.

6.1 Explosive Cladding of Short Gun Barrel Sections

6.1.1 Test No. Six:

Four short gun barrel sections were tested, three explosively, and one for I.D. surface fractures.

The first test conducted in this series is identified as Test No. Six.

For Test No. Six the stand-off distance and also the thickness of the explosive charge was excessive and caused catastrophic results.

6.1.2 Test No. Seven, No. Eight and No. Nine:

Two gun barrel sections were tested explosively, namely, No. Seven and No. Eight. The remaining gun barrel, No. Nine was inspected on the I.D. utilizing dye penetrant inspection techniques in search of surface fractures.

6.1.2.1 Explosive Testing:

Two gun barrel sections, Sample No. 7 and No. 8 were tested explosively utilizing the explosive bonding parameters as listed in Table X. For comparison purposes, the explosive bonding parameters which were utilized during Test No. Ten is also listed in this table.

TABLE X
EXPLOSIVE BONDING PARAMETERS

Test No.	Stand-Off In Inches	Explosive Charge Thickness In Inches	Explosive Charge Amount In Grams
7	0.190	0.75	2430
8	0.177	0.75	2256
10	0.177	0.75	6891

Before and after each test, the O.D. of the gun barrel was dimensionally inspected utilizing a Pi-Tape. The dimensions obtained together with the dimensional measurement made regarding the tooling is listed in Table XI.

TABLE XI
GUN BARREL O.D. MEASUREMENTS COMPARED
WITH TOOLING O.D. MEASUREMENTS

TEST NO.		DIMENSIONS IN INCHES				
		Outside Diameter		Wall Thickness		
		Gun Barrel	Tooling	(a) Gun Barrel	(b) Tooling	Total a & b
7	Before	7.675	12.840	1.148	2.583	3.731
	After	7.765	Nil			
	Delta-D	0.090	Nil			
8	Before	11.688	12.840	1.370	2.374	3.744
	After	11.736	Nil			
	Delta-D	0.048	Nil			
10	Before	12.673	16.030	3.660	1.464	5.124
	After	12.770	16.130			
	Delta-D	0.097	0.100			

The dimensions listed in the preceding table show the maximum dimensions obtained for each test. For Test No. Seven, the gun barrel sample showed diametric expansion ranging from 0.043-inch to 0.090-inch with an average diametric expansion measuring 0.070-inch. The sample obtained from Test No. Eight showed a diametric expansion ranging from 0.016-inch to 0.048-inch with an average diametric expansion measuring 0.029-inch.

Subsequent to dimensional inspections the sample from Test No. Seven was sectioned perpendicular to the axial center line at two places, thereby removing a section measuring one-inch long. This one-inch long section was sent to the Naval Ordnance Station for further evaluation.

The sample obtained from Test No. Eight was bisected perpendicular to the axial center line. The exposed surfaces were machined to RMS 63 finish and the bond interface between the steel liner and the gun barrel was examined utilizing dye penetrant inspection techniques. No evidence of voids at the interface was observed. However, fractures were found to exist in the gun barrel steel adjacent to the bond interface. These fractures measured approximately 0.093-inch long and extended radially from the bond interface toward the O.D. The fractures did not appear to traverse the bond interface nor did they appear to penetrate the steel liner. Therefore, it was assumed that these fractures were inherent in the parent gun barrel material prior to the explosive testing. In order to evaluate this assumption, gun barrel Sample No. Nine was examined on the I.D. utilizing dye penetrant inspection techniques. No evidence of fractures were observed, however.

6.2 Explosive Cladding of a Long Gun Barrel Section

A gun barrel section measuring 37.83-inches long was explosively clad internally with a steel liner having a 0.250-inch thick wall. This test is identified in the preceding tables as Test No. Ten.

Initially, the gun barrel section was dimensionally inspected and the findings compared with the measurements obtained subsequent to the explosive bonding test. The results of the dimensional examinations are listed in Table XII. See Page No. 17.

Referring to Table XII, the following observations are presented:

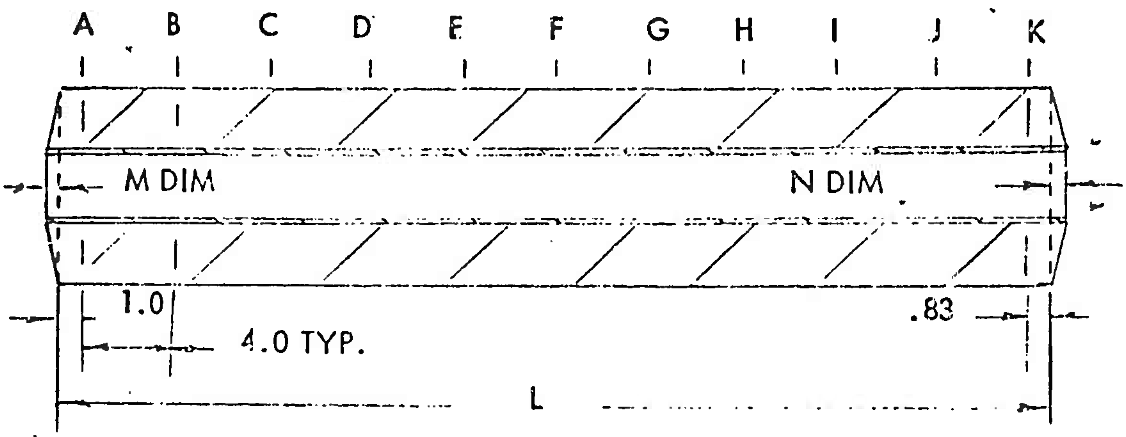
- The end of the gun barrel adjacent to the point of detonation was elongated diametrically less than the opposite end.
- The major diametric elongation occurred near the mid-point of the gun barrel.
- Linear measurement made along the O.D. of the gun barrel, L-Dimension, exhibited no change as a result of the explosive procedure.
- Material was extruded out of either end adjacent to the I.D. of the gun barrel. The end of the gun barrel adjacent to the detonation end M-Dimension, exhibited less metal extrusion than the opposite end, N-Dimension.

6.2.1 Bond Evaluation:

The gun barrel sample which was obtained during this final test was inspected ultrasonically to determine the integrity of the bond between the steel liner and the gun barrel. Figure No. 3 illustrates the results obtained from the ultrasonic testing. The following observations are presented.

TABLE XII

Measurements of Gun Barrel Section, 37-Inches Long



LOCATION	MEASUREMENTS IN INCHES		
	BEFORE	AFTER	DELTA-M
* A	12.671	12.712	0.041
B	12.672	12.709	0.037
C	12.672	12.715	0.043
D	12.672	12.742	0.070
E	12.672	12.758	0.086
F	12.672	12.768	0.096
G	12.673	12.770	0.097
H	12.673	12.766	0.093
I	12.675	12.750	0.075
J	12.675	12.720	0.045
K	12.675	12.725	0.050
L	37.830	37.830	-N[illegible]
M	---	0.093	0.093
N	---	0.140	0.140

* Adjacent to the point of Detonation

- The major portion of the total area measuring approximately 83% appears to be bonded. The remaining 17% of the area is divided into two areas as follows:

- Ten percent exhibiting sporatic bonding.

- Seven percent exhibiting unbonded area.

- The major unbonded areas were found adjacent to either end. Figure No. 4 shows the explosively clad gun barrel ultrasonically tested.

7. CONCLUSIONS

Based on the results obtained during this authorization, the following conclusions are presented.

- Five-inch gun barrels have been explosively clad with steel liners which were heat treated to hardnesses ranging from $R_c 27$ to R_c 32 Rockwell and having wall thicknesses measuring 0.250-inch thick.

- Explosive bonds between steel liners and gun barrels have been produced comprising 83% of the total area.

- Major unbonded areas appear to lie adjacent to either end.

- An explosive charge made from Trojan Dynamite measuring 0.75-inch thick and pressed to 20 grams.cu. in. is a candidate for explosively cladding steel liners to gun barrels.

- Further testing of tooling required to support the O.D. of the gun barrel during the explosive welding process is indicated by the resultant elongations observed in both the gun barrel and the tooling.

8.0 FUTURE WORK

Observations made during the current authorization indicate that further examinations of explosively lined gun barrels are imperative. The permanent deformation introduced into the parent gun barrel steel is apparent. The magnitude of the residual stresses should be investigated and recommendations for corrective action should be investigated.

8.1 Work Proposed

8.1.1 Gun Barrel:

The gun barrel structure should be examined before the worn surface has been removed and compared with the structure after the worn surface had been removed. Several inspection techniques are suggested as follows:

- o Penetrant
- o Magnetic Particle
- o Radiographic
- o Metallography
- o Micro hardness traverse
- o Ultrasonic shear wave techniques
- o Holography

The gun barrel structure should be investigated to determine its stress corrosion qualities before explosive cladding and compared with the structure after explosive cladding. This can be accomplished by examining the I.D. of the gun barrel with the worn surfaces intact by utilizing the inspection techniques described above. These same inspection techniques can be applied subsequent to the removal of the worn surfaces by machining. This will provide a known surface condition prior to explosive cladding. Upon completion of the explosive cladding procedure the investigation of the gun barrel structure would be divided into two categories as follows:

- o Fracture investigation
- o Stress level analysis

8.1.1.2 Fracture investigation:

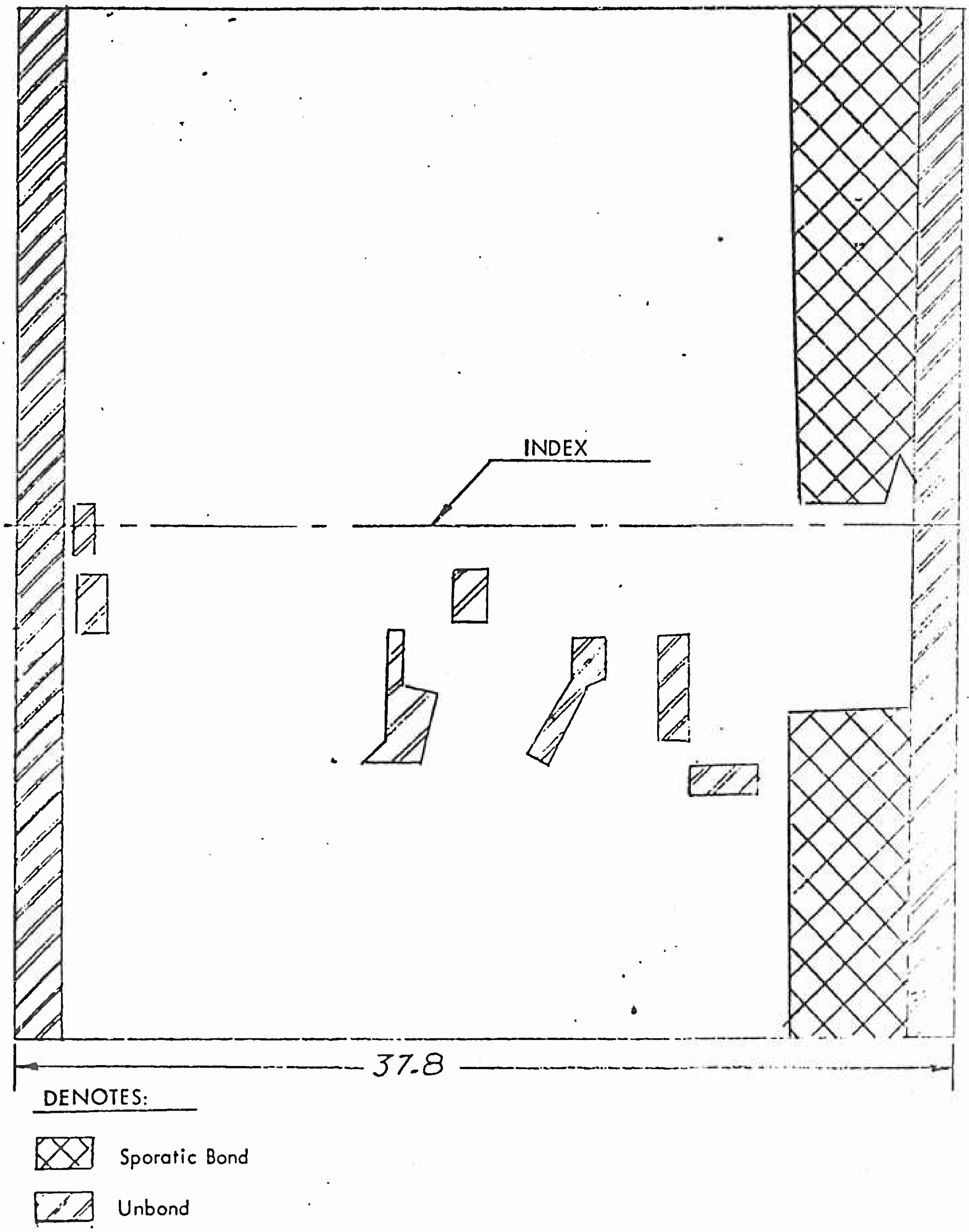
The explosively clad gun barrel can be examined both destructively and non-destructively to determine if any flaws or fractures are apparent in the structure. Any section containing apparent fractures may be removed from the gun barrel and examinined metallographically at high magnifications.

8.1.1.3. Stress Level Analysis:

Since permanent deformation was found to exist in the gun barrel subsequent to the explosive cladding procedure, the stress levels should be investigated. The resultant gun barrel can be investigated utilizing holography in order to express the stress levels quantitatively.

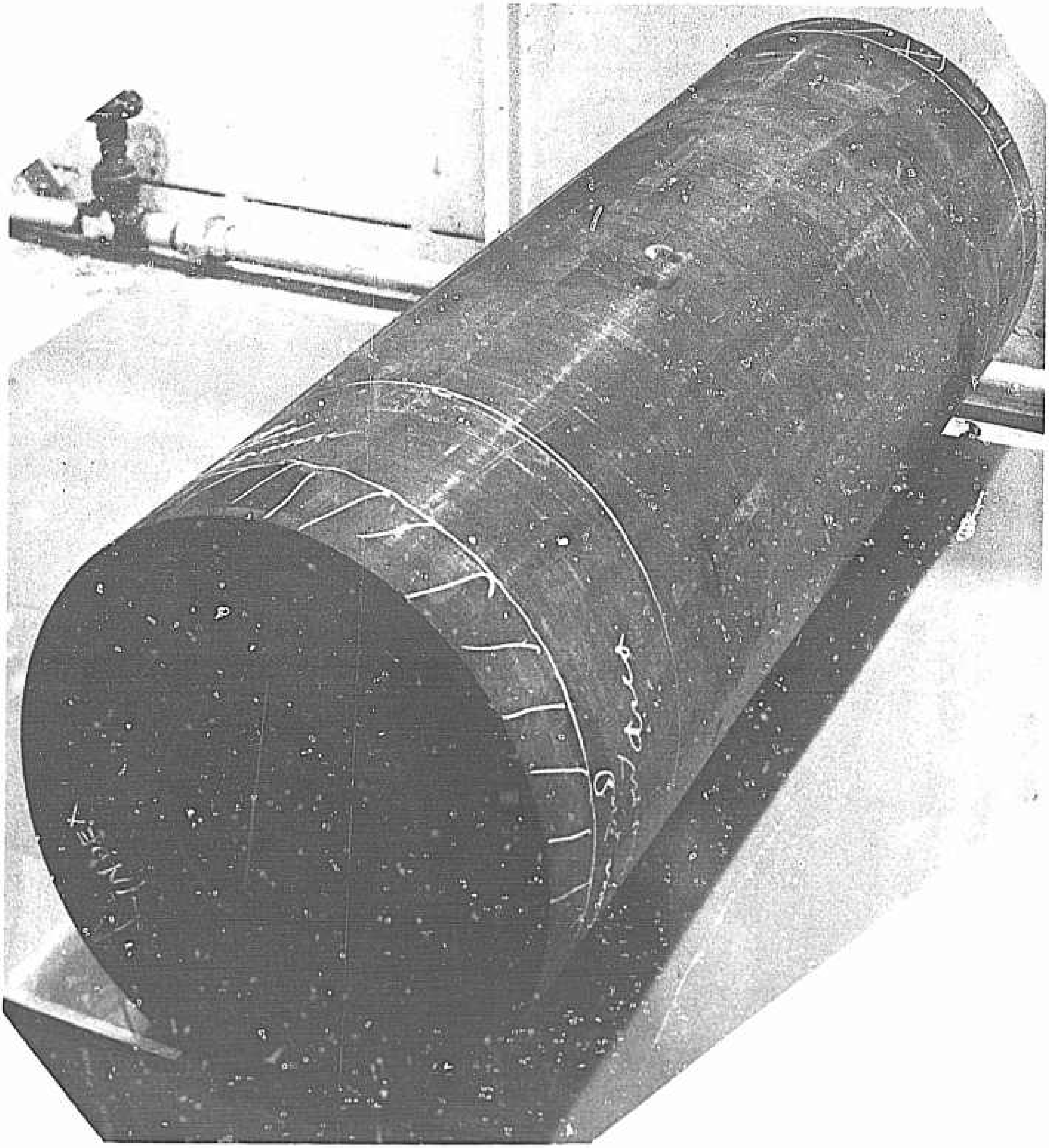
8.1.2 Steel Liners:

The steel liners should be investigated structure-wise to determine the effect of the explosive cladding procedure. The corrosion properties, the wear properties and the mechanical properties of the steel liners should also be established.



RESULTS OF ULTRASONIC TEST

FIGURE NO. 3



FIVE-INCH GUN BARREL EXPLOSIVELY CLAD INTERNALLY WITH A HEAT TREATED STEEL LINER

FIGURE NO. 4

APPENDIX C

EXPLOSIVE CLADDING A 4130 STEEL

LINER TO A 5" GUN BARREL

METALLURGICAL FINDINGS

The following tests were conducted by the Metallurgical Laboratory at NAVORDSTALOU to determine the chemical properties of inner bore material in new and used 5" gun barrels.

1. The metallurgical test was performed on three used and two new gun barrel sections. The age and history of the used gun barrel sections are not known. The two new gun barrel sections had not been fired.

2. The chemical analysis of all sections were similar except the new lined section were lower in nickel.

3. The microstructure examination revealed no difference between the inner and outer structures. However, there is considerable difference between the microstructures of the used and new gun barrels (see Figures 1 through 4). It is not possible to determine if the structure of the used gun barrels is due to original treatments or was changed by service use.

4. The microhardness traces revealed no change in hardness from inner to outer surfaces. However, the hardness range of the used barrels was 33-37 Rockwell "C" and the new barrels were 40-44 Rockwell "C".

5. The tensile test results are as shown in Tabulation of mechanical test data (Table 1). As you can see, there are considerable differences between the new and old gun barrels.

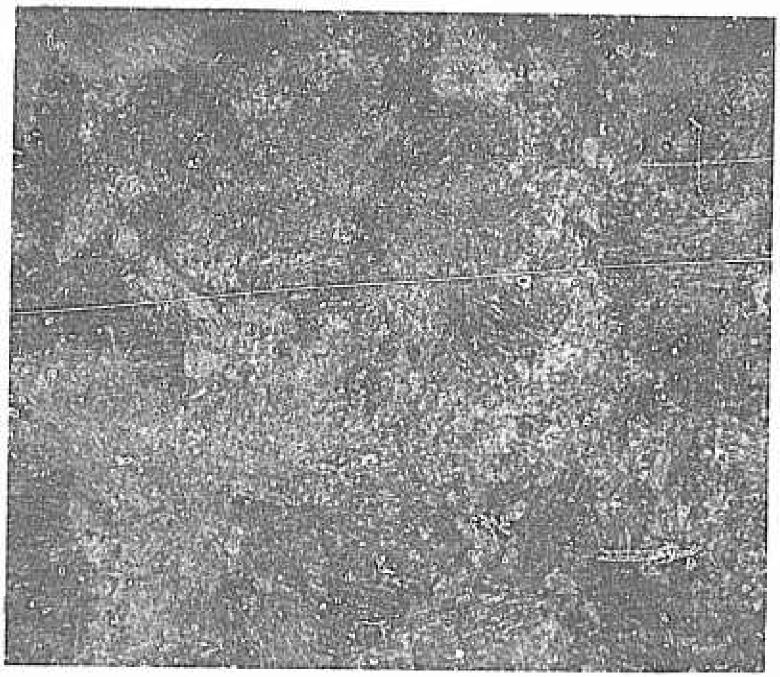


FIGURE 1 APPENDIX C
PHOTOMICROGRAPH OF STRUCTURE
OF USED GUN BARREL (ID, 10 x METAL ETCH)

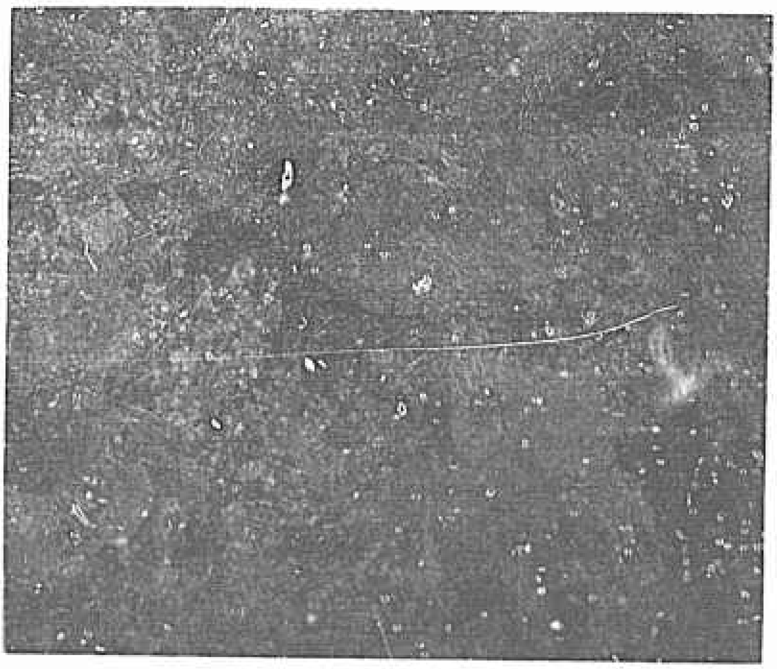


FIGURE 2 APPENDIX C
PHOTOMICROGRAPH OF STRUCTURE
OF USED GUN BARREL (ID, 100 X METAL ETCH)

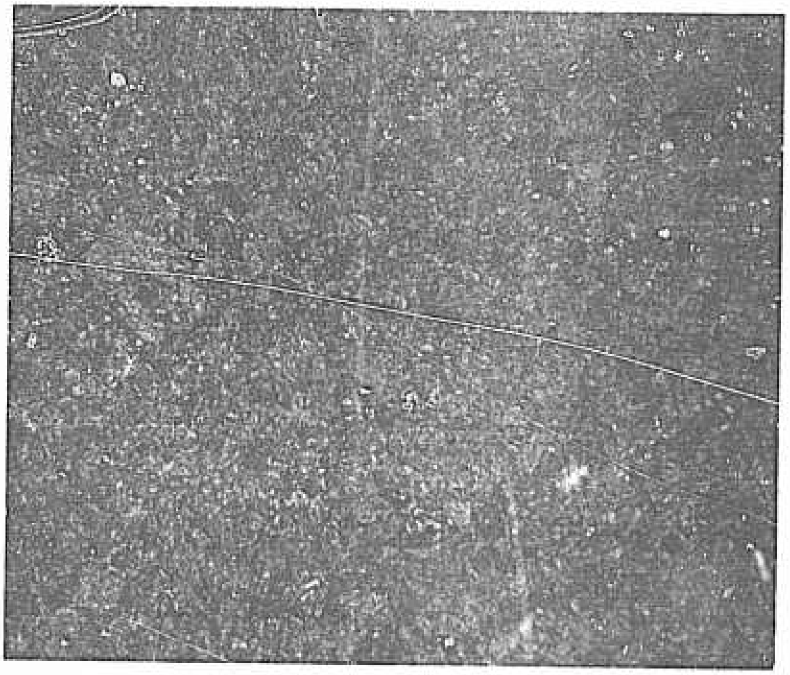


FIGURE 3 APPENDIX C
PHOTOMICROGRAPH OF STRUCTURE
OF NEW GUN BARREL (ID 10 X METAL ETCH)

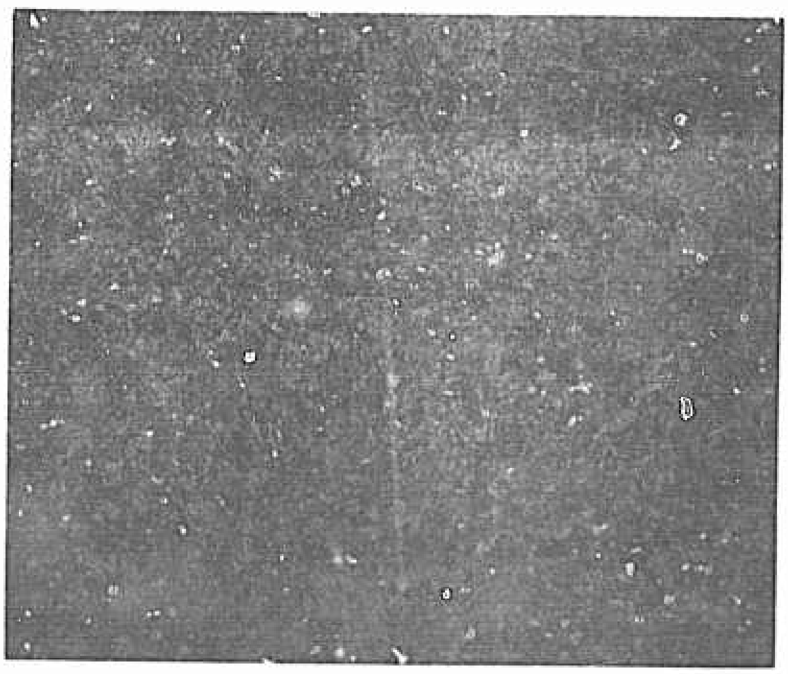


FIGURE 4 APPENDIX C
PHOTOMICROGRAPH OF STRUCTURE
OF NEW GUN BARREL (ID, 100, X METAL ETCH)

Gun Barrel Section*	Tensile Strength** Inside (psi)	Outside	Yield Strength Inside (psi)	Outside	% Red. Area Inside	Outside	% Elong. Inside	Outside	Hardness *** Rockwell C
1	145,365	145,497	129,466	118,992+	63.7	64.4	21.5	22.5	33 - 35
2	145,323	146,675	126,251	125,339	61.5	62.3	18.3	18.8	33 - 37
3	145,920	145,410	132,733	132,390	65.8	65.5	22.7	22.6	33 - 35
4	184,317	182,493	168,275	168,425	60.7	60.6	18.9	19.4	41 - 44
5	189,423	186,376	164,697	153,253	60.7	61.5	18.2	18.5	40 - 43

* 1. Used barrel, explosively lined experiment
2. Used barrel, explosively lined experiment
3. Used barrel
4. New barrel explosively lined experiment
5. New barrel

** All data, except hardness, is average of three samples

*** No hardness pattern between inside and outside

\+ Three samples with 10,000 psi variation, low to high

\# Three samples with 28,000 psi variation, low to high

TABULATION OF MECHANICAL TEST DATA

TABLE I - APPENDIX C